EFFECT OF CASTING TEMPERATURE AND CURING REGIME ON MECHANICAL PROPERTIES AND DURABILITY OF CONCRETE

BY

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عمادة الدراسات العليا
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Dedicated To

My Beloved Parents,

Mr. & Mrs. Muhammad Siraj

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THESIS ABSTRACT (ENGLISH)

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Under hot weather concreting, the primary cause of shorter service life of concrete structure is cracking. Cracking of concrete is noted in many structures of the Arabian Gulf where the environmental condition is characterized as hot weather. It could initiate a number of detrimental processes that are known to be harmful to the long-term concrete performance. High concrete temperature at the time of placement is one of the reasons of concrete degradation, especially under hot and arid environments. The cause of concrete deterioration is also ascribed to the high differential between the fresh concrete temperature and the ambient temperature.

To overcome the adverse effects of hot weather and to produce good quality concrete, many local building regulatory authorities and international codes of practice including the Saudi building code limit the maximum allowable fresh concrete temperature to 35°C. However, there is no data to validate this limit. Further, the applicability of this limit to blended cement concretes needs to be evaluated.

This study was carried out to evaluate the effect of water to cement ratio, casting temperature and curing regimes on the compressive and split tensile strength, pulse velocity, depth of water penetration and plastic and drying shrinkage strain of plain and blended cement concretes. The blended cements studied were fly ash (FA), very fine fly ash (VFFA), silica fume (SF), ground granulated blast furnace slag (GGBFS) and natural pozzolan (NP) and used at the following replacements: at 30, 10, 7, 70 and 20%, respectively, by weight of plain cement. The plain and blended cement concrete specimens were cast at temperatures of 25, 32, 38 or 45°C and cured under moist condition, covering with wet burlap or applying a curing compound. Plain concrete specimens were prepared with a w/c ratio of 0.3, 0.4 or 0.45 while blended cement concretes were prepared with a constant water to cementitious materials ratio of 0.4.

Results of this investigation indicated that the optimum casting temperature for OPC and SF cement concretes was 32°C while that for VFFA, FA, GGBFS and NP cement concretes it was 38°C. Further, moist curing was noted to be the most efficient curing regime for strength and pulse velocity development as well as for enhancing the durability followed by curing by covering with wet burlap and applying a curing compound, in decreasing order of importance. However, the application of a curing compound exhibited higher efficiency in reducing the plastic and drying shrinkage strain compared to curing by covering with wet burlap or plastic sheet. Based on the data developed in this study, the optimum concrete mixture temperatures for plain and blended cement concretes for hot weather conditions were presented. In addition, correlations between test properties and concrete mix parameters were developed along with the relationships among test properties.

ملخص الرسالة

الاسم: محمد ناصر

العنوان: تأثير درجة حرارة الصب ونظام المعالجة على الخواص الميكانيكية وديمومة الخرسانة

التخصص: الهندسة المدنية والبيئية

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تعتبر التصدعات السبب الرئيسي لانقاص العمر الافتراضي للخرسانة في البيئات الحارة. وقد لوحظ وجود تشققات الخرسانة في كثير من المنشآت في الخليج العربي والذي يتميز الحالة البيئية بالطقس الحار، مما يمكن أن يؤدي الى بدء عدد من العمليات الضارة، لأداء الخرسانة على المدى الطويل. ولذلك، تعتبر الحرارة العالية أثناء صب الخرسانة أحد الاسباب المباشرة في تدهور الخرسانة، وخاصة في البيئات الحارة و الجافة. كما يعتبر الفرق الكبير بين درجة الحرارة للخرسانة أثناء الصب و درجة حرارة البيئة المحيطة بها أحد أسباب التدهور في هذه المنطقة.

وللتغلب على الآثار السلبية للطقس الحار وإنتاج خرسانه ذات نوعية جيدة، فان العديد من منظمات البناء المحلية وكودات البناء العالمية ومن ضمنها كود البناء السعودي، تحدد درجة الحرارة القصوى للخرسانة الطازجة بـ 35 درجة مئوية. و للأسف، لا توجد بيانات للتحقق من صحة هذا التحديد. وعلاوة على ذلك، فان تطبيق هذا الحد لخرسانة الإسمنت المخلوط يحتاج إلى تقييم.

وقد أجريت هذه الدراسة لتقييم تأثير نسبة الماء إلى الاسمنت، درجة حرارة الصب ونظام المعالجة على قوة الضغط والشد، سرعة النبض، وعمق تغلغل المياه واجهاد الانكماش الجاف واللدن للإسمنت العادي والمخلوط. مع العلم بان الإسمنت المخلوط المستخدم في هذه الدراسة هو الرماد المتطاير (FA)، الرماد المتطاير الناعم جدا (FVFFA)، غبار السيليكا (SF)، وحبيبات خبث الفرن العالي المطحونة (GGBFS) والبوزلان الطبيعية (NP)، و التي تم استخدامها في الخرسانة بالنسب التالية: 30، 10، 7، 70، 20% على التوالي من وزن الاسمنت.

وتم صب العينات الخرسانية للإسمنت العادي والمخلوط في درجات الحرارة 25، 32، 38 او 45 درجة مئوية وتم معالجة هذه العينات بثلاث طرق هي: غمرها بالماء او عن طريق التغطية بالخيش الرطب او باستخدام المركبات المرطبة.

وتم إعداد عينات الخرسانة العادية باستخدام نسب الماء الى الاسمنت التالية: 0.3، 0.4 أو 0.45 في حين تم إعداد خرسانة الإسمنت المخلوط باستخدام نسبة ثابته للماء الى الاسمنت وهي 0.4. وأشارت نتائج هذه الدراسة أن درجة الحرارة المثلى لخرسانة OPC وخرسانات الاسمنت و SF كانت 32 درجة مئوية، بينما تلك لخرسانات VFFA, FA, GGBFS and NP كانت 38 درجة مئوية. وعلاوة على ذلك، لوحظ ان المعالجة بغمر العينات في الماء هي اكثر انظمة المعالجة كفاءة لزيادة

القوة وسرعة النبض وتعزيز الديمومة يليها بالترتيب التنازلي من حيث الأهمية المعالجة عن طريق التغطية بالخيش الرطب ثم وضع المركبات الرطبة. إلا ان تطبيق المعالجة المركب أظهر كفاءة أعلى في الحد من اجهاد الانكماش الجاف واللدن بالمقارنة مع المعالجة باستخدام الخيش الرطب او الورق البلاستيكي.

وبناء على نتائج هذه الدراسة، تم تحديد درجة الحرارة المثلى لخرسانة الاسمنت العادي والمخلوط، كما تم تطوير علاقات ارتباط بين نتائج الاختبارات وعوامل الخلطة الخرسانية جنبا الى جنب مع تطوير علاقات فيما بين نتائج الاختبارات المختلفة التي تم اجرائها في هذه الدراسة الاختبار.

درجة الماجستير في العلوم الهندسية
جامعة الملك فهد للبترول والمعادن
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المملكة العربية السعودية

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NOMENCLATURE

f_c	Compressive strength in MPa
f_t	Split tensile strength in MPa
PV	Pulse velocity in m/sec
DP	Depth of water penetration in mm
PS	Plastic shrinkage strain in microns
DS	Drying shrinkage strain in microns
w/c	Water to cement ratio
w/cm	Water to cementitious materials ratio
T	Concrete casting temperature in °C
t	Curing and/or exposure period in days
L	Low water permeability
M	Medium water permeability
H	High water permeability

CHAPTER 1

INTRODUCTION

1.1 Effect of Hot Weather on Concrete Performance in Local Environmental Conditions

Every year, a large number of concrete construction projects are executed under hot weather conditions in many countries around the world. Concrete was deemed to be a maintenance-free material until its deterioration has been reported from several parts of the world. Although the cost of repair and rehabilitation in the Arabian Gulf is not well documented but in general, it is estimated that hundreds of billions of US dollars are required annually to repair and rehabilitate the deteriorated concrete structures in different countries. Literature review shows that concreting under hot weather poses special problems.

The environmental conditions of the Arabian Gulf including the Kingdom of Saudi Arabia at large are characterized as hot weather, and can be classified as a hot-humid and hot-dry depending on the distance from the shoreline [1]. In these regions, deterioration of reinforced concrete is attributed to the following inter-related factors: (i) severe climatic and geomorphic conditions, (ii) poor quality of construction materials, particularly the aggregates, and (iii) inappropriate construction practices, particularly inadequate design specifications [2].

Hot months in harsh regions of Saudi Arabia, where the quantity of concrete cast everyday may be larger than that in any other parts of the world, are characterized by having maximum daily temperature in excess of 45°C, diurnal variations in excess of 20°C, relative humidity less than 15%, average wind speed of 6 m/s, and solar radiation of 600 w/m^2 [3].

The ambient temperature in these regions may be as high as 45 to 50°C in the summer. At this condition, the temperature on the concrete surface may be as high as 70 to 80°C due to solar radiation [4]. The persistent high temperature, rapid wind speed, solar radiation and concentration of chloride and sulphate salts in atmosphere, soil and groundwater are the predominant weather factors which make this region aggressive for concrete construction [5].

High monthly/annual mean temperature and wide diurnal variations have harmful effects on properties of concrete which lead to reduction in useful service life of the structures. The rate of water evaporation increases as the air temperature increases; for example, an increase from 10 to 20°C will result in the doubling of the rate of evaporation from the concrete [6].

High wind velocity and temperature tend to increases the drying of concrete skin. Therefore, the recommendations of ACI Committee 305 regarding minimizing the rate of water evaporation, such as lowering concreting temperature, increasing the humidity by water spraying, and erecting wind barriers, should be adopted [7].

Concrete mix design, including the selection of appropriate materials, significantly influences the performance of both fresh and hardened concrete. The main factor that contributes to the deterioration of concrete in the Arabian Gulf region is the quality of the locally available aggregates. Most of the aggregates available in the region are crushed limestones that are of marginal quality. These aggregates are porous, absorptive, relatively soft, and excessively dusty on crushing that cause higher water demand resulting in lower strength and greater shrinkage of concrete. Further, due to the large difference between the coefficient of thermal expansion of aggregate and hardened cement paste, tensile stresses are developed at the aggregate-paste interface tending to cause interface bond failure and significant micro cracking around the transition zone [8,9].

The high concrete temperatures at the time of concrete placement could initiate a number of detrimental processes that are known to be harmful to the short- and long-term concrete performance. The possible adverse effects of hot weather conditions on concrete quality may include [10]:

- Rapid evaporation of mixing water resulting in slump loss,
- Reduced concrete strength due to loss of mix water as a result of high temperature and low humidity, evaporation of curing water, non-uniform precipitation of the products of hydration between cement grains due to comparatively rapid hydration, micro-cracking as a result of strain incompatibility due to different expansions of concrete constituents,
- Reduction in the setting time of cement which creates difficulty in handling and finishing the concrete,
- Thermal cracking and increased plastic shrinkage cracking,
- Reduced durability,
- Formation of cold joints,

- Increased difficulty in controlling entrained air content, and
- Increased permeability.

The low durability of concrete in the hot and humid areas of the world has directed the attention of concrete technologists to search for concrete admixtures to improve the quality of concrete to cope with the aggressive exposure conditions. Research conducted earlier indicated the great potential of supplementary cementing materials in enhancing concrete durability. Among the SCMs researched, silica fume has displayed distinctly superior performance [11]. However, the use of supplementary cementing materials in the semi-arid and arid areas of the world, to improve concrete durability, deserves special attention for two reasons. Firstly, the climatic conditions of such regions make curing a difficult process and, secondly, in some places such as in the Arabian Gulf, these materials are used purely for their technical merits. As such, it is prudent to utilize these materials properly.

Curing of concrete is very essential for its strength gain and durability. Proper curing becomes very difficult under hot weather conditions as low humidity and high ambient temperature greatly assist in the evaporation of the mix-water. Concrete cast under hot weather and not sufficiently cured may show as much as 30 to 40% reduction in strength [12]. Curing becomes even more important if it contains supplementary cementing materials, such as fly ash, ground granulated blast furnace slag, or silica fume, and it is subjected to hot and dry environments immediately after placement and consolidation. However, concretes moist cured for only two days exhibited significant improvement in strength and other characteristics, as compared with concrete without any curing [13].

The durability, strength and other characteristics of concrete in hot climates are thus critically dependent on its treatment from the moment it is compacted. Inadequate curing can negate all the earlier care taken in mix design and concreting operations, and can also lead to serious defects such as plastic shrinkage cracking and excessive drying shrinkage.

Unless extraordinary precautionary measures are taken, concrete cast, placed, and cured in hot weather conditions will be of low quality [10]. Such low quality porous concrete significantly increases the ingress of chlorides, oxygen, moisture, and carbon dioxide to the steel surface. This situation is ideal for the initiation of reinforcement corrosion, especially if the cover over the reinforcing steel is of poor quality. Studies [14] conducted on the effect of temperature and humidity on reinforcement corrosion indicated that the rate of reinforcement corrosion is sharply increased by high temperature (greater than 20°C) and high humidity. The chloride permeability has been recognized to be a critical intrinsic property of the concrete. The chloride-induced corrosion of reinforcing steel manifest itself through cracking, spalling and delamination of the concrete cover, which eventually leads to the direct exposure of the reinforcing steel to aggressive environment [15]. One method to reduce this problem may be to stop the supply of oxygen, moisture, and other aggressive ions and gases to the steel surface, which are essential for reinforcement corrosion to occur. This can be achieved by designing good quality concrete and curing it properly.

The need to improve the quality of concrete in the Arabian Gulf is all the more important in order to minimize the prevalent corrosion deterioration problems in this region and to produce durable concrete. Construction practices significantly influence the performance of concrete, especially reinforcement corrosion. According to Rasheeduzzafar et al. [9], the following are the pre-requisite steps for producing efficient concrete:

i. Realistic evaluation of the service conditions,
ii. Formulation of materials specifications to match the severity of the service conditions, and
iii. Implementation of design specification and correct construction practices on site.

The above three requirements are highly interactive and constitute part of a holistic approach to increase durability. A deficiency at any of the above three stages will lead to a less durable concrete and its performance is bound to suffer.

In this research investigation, the effect of casting temperature and subsequent curing conditions on the mechanical properties, shrinkage, and durability characteristics of plain and blended cement concretes would be investigated. The outcome is expected to be beneficial to both the local and international construction industry and would be helpful in updating local codes of practices.

1.2 Significance of This Research

Cracking of concrete is noted in many structures in the hot weather conditions of the Arabian Gulf. Both plastic and drying shrinkage cracks accelerate the deterioration phenomena such as reinforcement corrosion. Further, the compressive strength of concrete is often reduced due to the crack propagation. According to literature, the properties of concrete are usually evaluated at laboratory conditions where concrete is cured at constant or variable (by artificial means) temperatures which do not simulate the fluctuating hot weather field conditions particularly those prevailing in most parts of

Saudi Arabia, Middle East and other countries having hot weather in summer. However, practically, concrete structures are exposed to continuous variation in climatic conditions. Therefore, there is a need to cast concrete at different temperatures in the natural environmental conditions and exposed for curing in the field by different means that are practiced and implemented on site. A significant amount of research work has been carried out on the curing of concrete at different temperature. While few studies have been conducted to evaluate the effect of hot weather conditions on the compressive strength of concrete, research is required to assess the effect of casting temperature and subsequent curing regime on the mechanical properties, shrinkage and durability characteristics of concrete. Further, the effect of hot weather conditions on the performance of blended cement concretes is not very well elucidated. This aspect also needs to be evaluated since almost all the concrete now incorporates supplementary cementing materials.

1.3 Objectives

The general objective of the proposed research was to evaluate the effect of casting temperature and curing regime on the mechanical properties, shrinkage, and durability characteristics of plain and blended cement concretes. The concrete mixtures were cast in the natural atmospheric conditions of hot weather and specimens were cured both in the laboratory and in the field. The developed data would be utilized to ascertain the suitable casting temperature and curing regime for the local environmental conditions with a view to enhance the performance of concrete.

The specific objectives of this study were the following:

i. To examine the individual and cumulative effect of concrete casting temperature and curing methods on the mechanical properties, shrinkage, and durability characteristics of plain and blended cement concretes, and

ii. To provide recommendations on the appropriate casting temperature and curing regime for the production of durable concrete under hot weather conditions.

CHAPTER 2

LITERATURE REVIEW

2.1 Hot Weather Concreting

Hot weather is defined as any condition (like high ambient or concrete temperature, low relative humidity, high wind velocity and solar radiation) that adversely affects the quality of fresh and hardened properties of concrete, during these environmental conditions, exceptional measures are required to be taken to ensure proper handling, placing, finishing, and curing of concrete [10]. Problems of concreting are most frequently encountered in the summer, but the associated climatic factors of high wind and dry air can occur at any time, especially in the arid or tropical climates. Specifications for concreting in hot weather conditions usually identify a temperature limit of 32°C to produce good quality concrete. However, this limit has been raised to 35°C in the recently formulated Saudi Building Code [13]. ACI Committee 305 for Hot Weather Concreting also limits the maximum allowable fresh concrete temperature to 35°C. To achieve this limit, the following precautions are recommended [10]:

i. Placement of concrete at lower temperature of the day, such as late afternoon, evening or night. If concreting is to be done at higher temperature, the following measures may be adopted: keeping aggregates cool by shading them or by spraying water over them, use of cold water for mixing and, if necessary, use of ice as part of the mixing water,

ii. Use of water reducing and retarding agents,

iii. Minimum mixing time and delivery time,
iv. Shortest possible time for placement, consolidation, and finishing, and
v. Proper curing of concrete by keeping it moist by making water available for hydration.

Some of these recommended measures are difficult to implement and when followed meticulously add to the cost of construction. Nevertheless, concreting has to be continuously carried out even at high ambient temperature pertaining to hot weather conditions. Furthermore, even if the concrete temperature is lowered to 35°C, there still remains the curing problem. Curing has to be carried out under hot weather conditions for at least seven days or even longer for blended cement concretes.

2.2 Curing of Concrete in Hot Weather

The objective of curing is to keep the concrete almost damp until the water-filled spaces, to a large degree, reduced by the products of hydration of cement [16]. Adding water to Portland cement starts a chemical reaction called "hydration", and produces a stone-like substance (i.e. the hardened cement paste). Hydration reaction is exothermic, which in combination with hot climatic conditions (such as low humidity, high temperature and persistent winds) can cause the concrete to dry out quickly and restrict the hydration reaction to incomplete. Further, it may induce thermal cracking and cause water inside the hydrating cement to "boil", thus creating bubbles which enhance the permeability of concrete. Josst and Reinhardt [17] reported that concrete mixes with the temperature ranging from 20 to 50°C increases the permeability by 13 to 62% and by 3 to 55% with an additional increase to 80°C. Both the rate and degree of hydration and the resulting concrete strength rely on the curing process that follows placing, consolidating and finishing of the plastic concrete. Hydration continues infinitely at a decreasing rate as long as water is present in the mixture and the environmental conditions are favorable. Once the water is removed, hydration ceases. In general, curing ensures that the mix water is available for hydration of cement. According to Powers [18], a minimum of 80% humidity is required for cement hydration. Moreover, he reported that the permeability of the surface layer of concrete may increase five to ten folds if concrete is inadequately cured.

A variety of curing methods are used in practice to prevent loss of moisture by evaporation from the concrete; they range from moist curing methods, such as water ponding and covering with wet burlap, where extra water is added to concrete, to sealing methods where the evaporation of water from concrete is prevented by the application of curing compound. As compared to water-retaining techniques, moist curing techniques are most effective and popular methods in which concrete remains fully saturated during the curing period. Also, curing compounds can be expensive than water. However, under the following circumstances it becomes necessary to cure concrete by the application of curing compounds:

- When potable water or burlaps required for curing is either costly or not easily accessible.
- When total expenditure of moist curing, including the cost of water and workmanship, especially repeated applications under hot environmental conditions, is greater than the cost of only one time applying a curing compound.
- When wet burlap curing is not beneficial, like in remote locations or when the curing under wet burlap cannot be prolonged due to construction constraints.

During curing period (i.e. duration from consolidation of concrete to the point concrete reaches its design strength), there should be certain steps taken to keep the concrete moist and as near to 32°C as practical. The properties of concrete, such as strength, water tightness, freeze and thaw resistance, wear resistance, and volume stability, improve with age as long as the moisture and temperature conditions favorable to continued hydration are maintained. The period can vary from a few days to a month or longer. For most structural purposes, the curing period for cast-in-place concrete is usually 3 days to 2 weeks. This period depends on such conditions as ambient temperature, cement type, mix proportions, size and shape of concrete mass, required strength and durability and so forth [19].

Loss of water from fresh and young concrete caused by inadequate curing can result in detrimental effects on the properties of concrete in the short and long run. These undesirable effects include appearance of plastic shrinkage cracks, reduction in strength, and increased permeability of harmful species due to porosity resulting in a shorter service life of the structure [10]. In many regions of Saudi Arabia, low humidity, high ambient temperature, persistent rapid wind speeds, and the solar radiation are the predominant hot weather factors. In such a weather where the loss of water from fresh and young concrete is greatly accelerated by the environment, the need for proper early moist curing is essential. Effective curing reduces the loss of water and increases the hydration of the cement and, hence, reduces the total porosity by continued formation of hydration products. Low permeability of concrete, on the other hand, is extremely important for the long-term durability of concrete. The lower is the permeability, the lower will be the ingress of deleterious substances in concrete. Moreover, curing has a significant effect not only on the fresh concrete but also on hardened concrete. It has been reported that proper curing reduces the concrete permeability and absorption characteristic [19].

2.3 Blended Cement Concrete in Hot Weather

Cement significantly influences the properties of the fresh and hardened concrete. The main properties that are affected by the type of cement are:

- Heat of hydration,
- Workability and its retention,
- Bleeding and settlement,
- Setting time, and
- Rate of early strength development.

While the type of cement influences the strength of concrete, it can also influence the following durability parameters:

- Corrosion of reinforcing steel caused by chlorides,
- Resistance to sulfate attack,
- Resistance to salt weathering, and
- Alkali-aggregate reaction.

The quantity of cement is also known to influence concrete durability. Rasheeduzzafar et al. [20] evaluated the effect of cement content on concrete durability and based on the results of that study, the authors suggested the following minimum cement contents:

- Foundations: 350 - 375 kg/m^3

- Super-structures exposed to direct marine influence: 350 - 375 kg/m^3
- Super-structures not exposed to direct sulfate/chloride attack: 325 - 350 kg/m^3

The importance of minimum cement content for the production of durable concrete is now recognized by the international codes of practice and limits on these values based on the service environment are recommended [21]. Increasing the cement content will increase the heat of hydration thereby accelerating the possibility of developing shrinkage cracks, particularly in the hot weather conditions of the Arabian Gulf.

Cement is a key constituent of concrete constructions. A world without Ordinary Portland Cement (OPC) can hardly be expected. However, the cement industry is dealing with a number of unprecedented challenges that include depleting fossil fuel sources, lack of raw materials, continually increasing demand for cement, escalating environmental influences due to climatic changes and unstable world economy [22]. Researchers of civil engineering field are suggesting the world to use sustainable materials for green construction because of the following reasons [5]:

i. The large amount of waste that is disposed to landfill annually,
ii. The global impoverishing of natural resources and environments, and
iii. The emergency of carbon dioxide emissions.

In this regard, the usage of supplementary cementitious materials (SCMs) or environmental-friendly concrete has gained popularity. SCMs consist of raw materials, such as industrial, agricultural and domestic waste, recyclable material and even earth (that are cheap and abundant almost everywhere). The increased use of and interest in SCMs is also due to:

i. The reliance on foreign imports for cement would decrease because construction boom in many countries of the world has raised the consumption of cement more than their production. For example, according to Portland Cement Association (PCA), the domestic cement production of USA in 2003 was about 85 million tons while the demand was 107.5 million tons [23]. Also, the Saudi government, on April 16, 2013, ended the ban on cement import for one year and has permitted to import 10 million tons of clinker to overcome the shortage of locally produced cement [24].

ii. The amount of energy required by the cement manufacturing industries and production of greenhouse gases would be reduced [25]. Manufacturing of every ton of OPC leads to emission of about same amount of CO_2 into the atmosphere. It is estimated that cement plant releases 40% of CO_2 from the combustion of fossil fuel during kiln operation, production process emits 50% CO_2 while the rest of 10% emission occurs at the time of transporting the finished product to the site [26]. In developing countries, the rate of CO_2 emission is continuously increasing because of population growth and industrial revolution, which is a serious threat to future generation and prosperity on the earth [27].

iii. The desire of industries to exempt from green taxes and to avoid fuel price hike which will help to stabilize the cost of cement bags and control economy [22].

During the late 1980s, pozzolanic materials for improving concrete durability were introduced to the construction industry [28]. SCMs are used in concrete mainly as fillers or due to their pozzolanic characteristics [22]. It means that the hydration of SCM particles will be same as Portland cement, by providing substantial silicate in the mixture to react with the extra hydrated lime discharged during the Portland cement hydration.

The advantages of incorporating SCMs as partial replacement to the cement include: (i) refined and discontinuous pore structure resulting in improvement in strength and impermeability of hardened concrete to water and other aggressive species, (ii) increased resistance to sulfate and acid attack, (iii) minimum risk of alkali-silica reaction and (iv) reduction in amount and rate of heat evolution which is beneficial in mass concreting [29]. Some of the most commonly used SCM's manufacturing process and properties are described in the following paragraphs:

Fly Ash (FA)

Fly ash, also known as pulverized fuel ash, is a by-product of coal or other solid fuel combustion systems mainly used for electricity generation. Where bottom fuel ash is left in the region of combustion, fine grained fly ash is carried with combustion fuel gases and usually captured by electrostatic precipitation process. The chemical composition of fly ash tends to be a heterogeneous mixture of silicon oxides (SiO_2), aluminum oxides (Al_2O_3) and iron oxides (Fe_2O_3, Fe_3O_4) [30].

Because of its pozzolanic properties, fly ash is often used to replace typically 30% of the mass of Portland cement in a concrete mix, for example to lower permeability and reduce initial heat evolution. Fly ash may contribute to the strength of concrete after seven or more days of curing. Strength development of fly ash in concrete is due to a chemical reaction between the fly ash and calcium hydroxides produced by hydration of OPC [31]. Because of the slow reaction of fly ash in the concrete, it is reported by Neville [32] that, at early ages, the concrete containing fly ash has a higher permeability than plain concrete with a similar w/c ratio. However, Fraay and Bijen [33] reported that with time, fly ash concrete acquires a very low permeability.

Ground Granulated Blast Furnace Slag (GGBFS)

This is a by-product of the iron and steel mills; while pig iron is extracted from melted raw iron ore, the residue material (which floats to the top) is referred to as slag. It consists of calcium, magnesium aluminosilicates and also has pozzolanic properties depending on quenching history and cooling method used. Granulated slag is formed by quickly quenching molten iron slag with water. The result is glassy sand-like material that, when granular product is ground to a fine powder and contacted with alkali such as lime or Portland cement, develops strong hydraulic cementation properties [34].

Natural Pozzolans (NP)

Natural pozzolan is a raw or calcined natural material that has pozzolanic properties. It is one of the oldest materials used for construction purposes by blending it with lime. Its sources are volcanic ash or pumice, shale, tuffs and some diatomaceous earths [35].

Initial studies conducted at KFUPM have shown that the pozzolanic activity of this indigenous material is low and as such it does merely meet the ASTM C 618 requirements as a pozzolanic material [36]. NP fineness and source did not affect compressive strength. Hot curing is very beneficial for strength development and for improvement in chloride permeability [37]. Hence, utilization of locally available NP in hot weather regions of the Kingdom of Saudi Arabia is very favorable.

Silica Fume (SF)

Silica fume, also known as micro-silica are essentially one and the same; is a by-product of the production of silicon and ferrosilicon alloys in electric arc furnaces. Addition of SF to cement results in a stronger and durable concrete than other blended cement concretes. It also reduces the permeability of concrete and, hence, provides better protection to steel reinforcement. One drawback of using silica fume is the increased water demand and, therefore, many codes limit the replacement level to around 6% unless the mix contains high dosage of superplasticizer. Although in early days, silica fume was a cheap waste product, it is now an expensive high performance cement supplement primarily used in structures exposed to aggressive environments.

A study performed by Khatri and Siriviratnanon [38] indicated that the addition of silica fume to Portland cement concrete marginally decreased its workability but significantly improved its compressive strength at all ages. The unique qualities that make silica fume handy in improving the concrete performance are [39]:

i. Its particle diameter is 100 times finer than that of ordinary Portland cement,
ii. Its spherical shaped particles increase the lubrication effect in the cement,
iii. Its glassy particles enhance its reactivity with cement, and
iv. Its high amorphous silica content (about 90%) makes it a superpozzolanic material.

Early researches on the use of SCMs, such as fly ash and blast furnace slag, in the Arabian Gulf were carried out at King Fahd University of Petroleum and Minerals. These studies [42,43] revealed that satisfactory characterization of SCMs is necessary, since all SCMs did not perform as expected. Following studies were related with the use of silica fume, fly ash, and blast furnace slag to increase concrete durability. It was concluded from the results [44,45] that incorporating these materials to cement can greatly improve the durability of concrete. It was revealed that from the industrial by-products examined, silica fume performed better than others.

However, concerns were existed about the behavior of silica fume cement concrete in magnesium sulfate-bearing soil and groundwater [46,47]. The second concern is the increased plastic and drying shrinkage of silica fume cement concrete under hot and arid climates [48,49]. Shekarchi et al. [48] studied the long-term chloride diffusion in silica fume cement concrete in harsh marine environment. It was noted that partial cement replacement level, up to 7.5%, with silica fume reduced the coefficient of chloride diffusion significantly while higher replacement levels slightly decreased the diffusion coefficient [48].

The use of supplementary cementing materials, such as silica fume, fly ash, blast furnace slag, and natural pozzolans, has been encouraged by the concrete technologists for their technical and economic advantages [49]. However, the use of supplementary cementing materials in the hot and humid areas of the world, to achieve acceptable strength and enhance concrete durability, requires special care regarding their water demand, curing method and duration. Curing is also essential for the pozzolanic cement concretes as water is required for the pozzolanic reaction. Despite some SCMs require less water, others increase their water requirement to give the desired workability. Hence, for a reasonable comparison of the properties of blended cement concretes, it is essential to design concrete with same workability. Also, effects of curing method and their period on the performance of blended cement concretes is another concern because unlike OPC concrete, these concretes need early and extended curing. The quality of curing water is another important factor for making durable concrete. If concrete is improperly cured, the permeability of the surface layer may be increased by more than five times.

The harmful effects and precautionary measures required to be taken, when curing has been carried out in the hot weather particularly with SCMs, are reported and suggested by several authors including:

i. Proper curing of concrete becomes more essential under hot weather conditions with increasing use of SCMs, such as silica fume. Due to high pozzolanic reactivity of silica fume, the chances of plastic and drying shrinkage of such concrete is also increased if it is inadequately cured. Due to insufficient curing to silica fume cement concrete, several problems of cracking have been reported from the field [53,54].
ii. Blended cements are increasingly utilized to improve concrete durability. Several research studies carried out at King Fahd University of Petroleum and Minerals on the use of supplementary cements have indicated the superior performance of these cements in mitigating reinforcement corrosion [55–60]. However, the main cause of concern for the use of these blended cements, particularly silica fume cement, has been the need for extended curing and the tendency for the formation of plastic and drying shrinkage cracks.
iii. Partial cement replacement with GGBFS offers the potential to produce stronger and more durable concrete in hot climates. The disadvantage of GGBFS concretes is that they proved to be more sensitive to poor curing than OPC concrete. In this case, both their strength and permeability and, hence, their durability, were

seriously impaired. Therefore, special care must be taken when using this type of concrete, especially on site, where the working conditions and the application of curing are not as easy to control as in the laboratory [58].

iv. Due to the use of GGBFS in concrete mixes, the hydration process is slower than the OPC concrete mixes and concretes containing GGBFS require more curing period than OPC concretes [59].

v. In general, longer periods of initial curing are essential for concretes in hot weather, and especially for those that contain natural pozzolan (a period of more than seven days is necessary) [60].

vi. The use of fly ash involves greater plastic shrinkage and thereby increases the vulnerability of the concrete to plastic shrinkage cracking. Hence, when fly ash is used, extra care should be taken in order to prevent such cracking by protecting the fresh concrete from drying as soon as possible after being placed and finished [61].

2.4 Effect of Hot Weather on Properties of Concrete

Most parts of Saudi Arabia are included in the typical environment classified as hot weather. In these regions, summer day temperature is frequently in excess of 40°C. The humidity is low in the central region of the Kingdom of Saudi Arabia and it varies from very low to high in the coastal flats within a short span of time. The contrast between night and the maximum day temperature and humidity is large. Therefore, hot weather not only creates difficulty while casting, placement, consolidation, finishing and curing of concrete but also influence the fresh and hardened properties of concrete.

Mouret et al. [62] investigated the influence of temperature on the physical and chemical properties of hardened concrete. Concrete specimens were cast in summer conditions and using physical and chemical tests, the reasons for the decrease in the 28-days strength of concrete was found. In their study, scanning electron microscope (SEM) showed air bubbles and calcium hydroxide crystals which indicate the decrease in strength in some cases. Porosity and water absorption were reported to increase under hot weather while the degree of hydration was not influenced.

Hale et al. [63] examined the influence of curing temperature on fresh and hardened properties of plain and supplementary cement concrete. The cementitious materials included ordinary Portland cement (OPC), 20% fly ash (FA) and 25% blast furnace slag (BFS). At first, concrete was cured at elevated temperature (mixed at 32 - 37°C and cured at 37.7°C for first 12 hours and then cured at 28.3°C in water until testing). Secondly, concrete was cured in cold weather (mixed and cured at 10°C for first 24 hours and later on cured at 10°C in water). Third curing regime was standard curing (mixed and cured at 23°C and later also cured in water at 23°C). The results showed that introduction of BFS and FA slightly decreased and increased slumps, respectively, as compared to OPC concretes. It was noted that setting time decreased with increase in mix temperature of all mixtures while final setting time of cold weather concretes were about twice of those mixtures cast at standard temperature. The compressive strength of concrete cast with FA tended to reduce than OPC concrete mixes while compressive strength of GGBFS containing mixtures increased as compared to OPC concrete mixes at all curing regimes.

Soroka et al. [61] studied the harmful effects of elevated temperatures on the characteristics of fresh concrete, notably water cement ratio, setting time, rate of slump loss and plastic shrinkage using retarders and fly ash. They concluded that under hot climatic conditions, the use of Class F fly ash along with Type D admixture is advisable. This admixture was found to increase the rate of slump, but good for reducing water requirement and for delaying setting times. Fly ash, on contrary, helps reduce the rate and degree of slump loss. Both fly ash and retarders prove to raise the vulnerability of fresh concrete to plastic shrinkage cracking.

Al-Negheimish and Al-Hozaimy [64] studied the variation in slump and concrete temperature, during transportation of ready mixed concrete (RMC) under the very hot and dry weather of Riyadh in central Saudi Arabia. A total of 80 delivery trucks were tested including three plants employing a truck-mixing method and three plants using a central-mixing method. They reported that changes in the characteristics of RMC while delivery under the hot weather conditions were not much different than those for a milder summer typical in the mid-western U.S. The results indicated that during delivery in the summer period, by an average of 1.1°C of concrete temperature was increased and slump loss was 37% of its initial value. The in-situ compressive strength was slightly higher than that at the plant and was not significantly changed by long transportation time. According to the authors, as per ACI 305R specifications, the use of water-reducing and retarding admixtures as well as limiting concrete temperature and avoiding delivery during noon hours were shown to be effective in controlling the detrimental effects of hot weather on the production and delivery of concrete.

Baluch et al. [65] studied the effect of hot weather conditions on mass transport properties of concrete including convective moisture transfer coefficient and moisture diffusivity. With the help of experimental and numerical method the adverse effect of different temperatures (35 to 70°C) and wind speed (22 km/h) on moisture loss, moisture diffusivity, and convective transfer coefficient in concretes with three water to cement ratios was examined. Based on the results obtained in that study, some invariant functional forms were postulated, such as moisture loss, free shrinkage, and average moisture diffusivity. In addition, the results were also used for inventing model for a minimum crack mix design.

Ahmadi [66] carried out a study on the effect of hot weather on the initial and final setting time of concrete. The influence of field temperature, relative humidity, wind velocity, and admixture on setting time of concrete was evaluated. It was reported that the weather conditions affected both the initial and final setting time of concrete. It was observed that the initial setting time of concrete decreases with the increase in field temperature and wind velocity, while initial setting time tends to increase with the increase in relative humidity. Two correlations for predicting the initial and final setting times of concrete in hot weather were developed.

Mouret et al. [67] conducted a research to determine the influence of aggregate temperature on the compressive and split tensile strength of plain cement concrete. Concrete specimens were cast with several aggregate temperatures between 20 to 70°C and cured under either laboratory condition (at 20°C) or simulated hot climatic condition (at 35°C). It was noted that both the 28-day compressive and split tensile strength of concrete were decreased with an increase in the aggregate temperature by 15 and 17%, respectively. The rise in aggregate temperature also tends to increase the water requirement of the concrete mixture.

Ait-Aider et al. [68] studied the effect of w/c ratio on the compressive strength of concrete under hot climatic conditions. Under normal conditions, an increase in w/c ratio tends to decrease concrete strength. However, they reported that in hot weather, increase in water content would not provide the same result. This amount of extra water can provide adequate moisture for the hydration reaction maintains workability and compensate simultaneously mixing water lost due to evaporation. This research indicated that under hot weather conditions, the increase in the w/c ratio, up to a certain extent, has no pronounced effect on the strength of concrete.

Hasnain et al. [69] assessed the effect of evaporation of water from fresh concrete in hot weather conditions of Jeddah, western Saudi Arabia. The concrete specimens were cast with surface area of 0.1 m^2 while maintaining the casting temperature of about 32°C. The specimens were cast in the morning, noon or early afternoon time and cured in the field by shading or in open air. The results indicated that the maximum rate of evaporation exceeded the limiting value of 1.0 kg/m^2-h for all casting time. Generally, the maximum evaporation rate occurred in the first hour if concrete is cast in the noon and afternoon time while the maximum rate of evaporation took place 3 to 5 hours later if the mix is cast in the morning time. It was further noted that 50% rate of evaporation decreases when concrete specimens were shaded as compared to those concrete samples which were kept in open air during day time.

Ortiz et al. [70] studied the effect of mixing time on workability and compressive strength of concrete under hot and cold weather environments. The study focused on variables such as concrete mixing hour and five distinct mixing hours were adopted for both climatic conditions. The results for compressive strength showed that the best mechanical performance of concrete, under hot weather conditions, took place when there was a minimum difference between concrete temperature and ambient temperature i.e. during the later hours of the day.

Kayyali [71] studied the influence of some mixing and placing practices on the strength of concrete under hot weather conditions. The parameter studied were different methods of compaction, vibration time, mixing time and delay between mixing and placing. The concrete specimens were cast at an average temperature of 32°C and relative humidity of 20% using ordinary Portland cement. It was found that prolonging mixing time and delaying casting up to 40 min increases the concrete strength of about 23% without significant loss in workability, provided that curing is done properly. It was also noted that vibration time should be kept to about 10 sec for achieving higher strength. The author concluded that if such effects are considered while casting, it is likely that no special measures are needed to reduce the temperature of the fresh concrete mix.

Alshamsi et al. [72] investigated the influence of mixing duration and season of casting on the drying shrinkage of normal strength concrete. The concrete mixtures were prepared and tested in outdoor condition of Al-Ain city (interior region in the UAE). Each mix was cast twice, once in the summer and once in the winter. The specimens were cast, cured and kept in the field condition. All the specimens were kept in natural environmental condition after curing for three days. Drying Shrinkage was then immediately measured. The influence of mixing duration was also determined by casting concrete specimens at 20, 40 and 60 minutes from the beginning of mixing. The cementing materials used were OPC and OPC plus silica fume. The authors reported that drying shrinkage has great effect on season of casting. However, the duration of mixing did not influence the drying shrinkage of both OPC and silica fume cement concretes.

Almusallam et al. [73] investigated the combined effect of mix proportions, i.e. water to cement ratio and cement content, on plastic shrinkage cracking of concrete in hot environments by measuring the water evaporation, bleeding rate, and time and intensity of cracks. The authors reported that cement content and water-cement ratio greatly influence the plastic shrinkage of concrete. Further, rich-plastic concrete mixes cracked after the lean-stiff concrete mixes. The intensity of cracks in the former was found to be more than that in the latter. It was indicated that plastic shrinkage cracking appeared when the evaporation rate was in the range of 0.2 to 0.7 kg/m^2-h, as contrast to a value of 1 kg/m^2-h recommended by the ACI 305. The rate of evaporation and bleeding was reported to be lowest in a lean-stiff concrete mix prepared with a cement content of 300 kg/m^3 and a water to cement ratio of 0.40, showing that this mix composition can be effectively considered to minimize plastic shrinkage cracking in hot weather.

Al-Amoudi et al. [49] studied the performance of plain (OPC) and certain supplementary cementing material like 7.5% silica fume (SF), 30% fly ash (FA) and 10% very fine fly ash (VFFA) by conducting compressive strength and pulse velocity tests after exposing the concrete specimens to sulfate solutions and moisture and thermal variations. A constant workability of 75 to 100 mm slump in concrete mixtures were maintained. The compressive strength of SF, FA and VFFA cement concretes was greater than that of OPC concrete. Further, maximum compressive strength was observed in VFFA and FA cement concrete. The compressive strength of OPC and all blended cement concretes, exposed to thermal variation (70 to 25°C), increased with an increase in the number of thermal cycles. On contrary, the pulse velocity decreased with the number of thermal cycles. The influence of curing condition, specifically water ponding and application of curing compound, was also determined. It was recorded that the water demand of FA and VFFA cement concretes was less than that of OPC and SF cement concrete. This reduction has resulted in better strength and durability of FA and VFFA cement concretes.

Almusallam et al. [74] examined the effect of different environmental exposure at the casting period on the characteristics of fresh and hardened concrete specimens. The specimens were exposed to temperature (30 and 45°C), relative humidity (25, 50 and 90%) and wind velocity (0 and 15 km/h). The specimens were kept in the exposure chamber for 6 h after 24 h, the samples were taken out from the chamber and kept in the field condition. Further, the specimens were covered with wet burlap or plastic sheet for curing up to 28 days. The results indicated that the increase in temperature and wind velocity and decrease in humidity caused increase in evaporation rate and shrinkage strain. Also, plastic shrinkage cracks were appeared earlier at low humidity and elevated temperature exposure of concrete specimen compared to those exposed to high humidity and low temperature. Likewise, cracking was noted earlier in windy conditions than those exposed to no wind concrete specimens. Further, compressive strength and pulse velocity decreased in elevated temperature exposure and these values were higher in concrete specimens cast at 30°C than 45°C.

Wang et al. [75] investigated the behavior of membrane curing and observed that the performance of such curing chiefly depends on its application time. The authors suggested applying the curing compounds at the earliest possible time after placing concrete. The results indicated that among the curing compounds tested, effectiveness of type of curing compound in increasing order were water-based type followed by solvent-based and then chlorinated rubber.

Al-Amoudi et al. [46] investigated the exposure of hot weather conditions on the plastic shrinkage of concrete specimens made with plain and silica fume (of different types and dosages) cement concrete. Silica fume was obtained from five sources, one of which was undensified and remaining four types of silica fume were densified. Dosages of silica fume used by weight of cement were 5, 7.5 and 10%. Maximum plastic shrinkage was reported in the concrete specimens cast with undensified silica fume at all dosage of silica fume. Plastic shrinkage strain in all types and dosages of silica fume concrete samples were greater than those in plain cement concrete samples.

Fattuhi and Al-Khaiat [28] exposed concrete specimens to natural environmental conditions in Kuwait and conducted a long-term analysis on the drying shrinkage. 52 concrete mixes were cast and the specimens were exposed to field condition after 28 days of laboratory curing (water or air curing). Parameters studied include water to cement ratio, type of cement, type of pozzolanic material, type and dosage of admixture, curing duration, and type of curing aid and special coating. The normal and high range water reducers and retarders were used as admixtures. Drying shrinkage results were recorded up to 726 days of age. The authors observed that no particular admixture had adverse effect on the drying shrinkage of concrete while effect of dosages of admixture requires further investigation. Moreover, the addition of silica fume, fly ash or white cement in the concrete mix caused reduction in the drying shrinkage. It was also concluded that in lowering the drying shrinkage, some of the curing compounds/aids and special coatings utilized were more useful than others.

MA Bao-guo et al. [76] measured the drying shrinkage property of cementing materials like 100% OPC or 5 and 10% Silica Fume (SF) or 10 and 30% fly ash (FA), at varying w/b ratios (such as 0.3, 0.4, 0.5 or 0.6), under constant temperature of 20°C and humidity ranging from 50 to 100%, after 28-days of water curing to prism specimens. The results indicated that at lower w/b ratio and relative humidity, drying shrinkage of mortar specimens decreases. The inclusion of SF, under higher humidity, reduces the drying shrinkage due to more refined pore structure of mortar with SF. The addition of FA, under different environmental conditions, increases the drying shrinkage due to increase in porosity of mortar with FA.

Al-Amoudi et al. [77] measured plastic shrinkage of plain and silica fume cement concrete and monitored the effect of different Superplasticizers and silica fume. The type of superplasticizers includes polycarboxylic ether (PCE), modified lignosulfate Polymer (MLP), sulfonated naphthalene polymer (SNP), and sulfonated naphthalene formaldehyde (SNF). Silica fume used were procured from three producers from which, one type was undensified and other two were densified. The concrete slab specimens with a constant slump were cast and cured in an exposure chamber where the temperature, relative humidity and wind velocity were maintained at 45 ± 2°C, 35 ± 5%, and 15 ± 2 km/h, respectively. It was noted that resistance to plastic shrinkage cracking improves in silica fume concrete with the use of Superplasticizer. The results also showed that undensified silica fume concrete attained the highest plastic shrinkage strain for all types of Superplasticizers used while plain cement concrete developed lowest strain.

Al-Amoudi et al. [78] evaluated the influence of specimen dimensions and curing regime on shrinkage and mechanical properties of plain cement and silica fume concrete specimens prepared and cured outdoor under hot weather conditions. Results indicated that the plastic shrinkage strain in the silica fume concrete specimens was 70% (on average) greater than that in plain cement concrete specimens. Drying shrinkage in silica fume concrete specimens were also more than those in plain cement concrete specimens. Further, plastic and drying shrinkage in both plain and silica fume cement concrete specimens cured by covering with wet burlap was found greater than those cured by continuous water ponding. The compressive and split tensile strength and pulse velocity were measured up to 180 days and found to increase with age. These values were more in silica fume cement concrete specimens as compared to plain cement concrete specimens. Also, these values in specimens cured by water ponding were greater than those concrete specimens cured by wet burlap. The authors suggested that cracking of concrete due to plastic and drying shrinkage can be prevented by selecting good quality silica fume and curing regime, especially under hot weather.

Alsayed [3] studied the effect of different curing regimes on the properties of concrete exposed to adverse climatic conditions of Riyadh. The curing methods include, covering with burlap and spraying water twice a day (method #1), no covering with sprinkling water twice a day (method #2), covering with impervious polythene sheet (method #3) and air curing (method #4). The properties of concrete measured by the experiments include compressive strength, modulus of elasticity, porosity, water absorption and shrinkage. The results indicated that compressive strength was highest in concrete specimens cured by curing method #1 followed by #2, #3 and #4. Water absorption was noted maximum in concrete specimens cured by curing method #4 followed by #3, #1 and then #2. Shrinkage was measured maximum in concrete specimens cured by curing method #4 which was followed by method #3, #1 and then #2. It was concluded that for strength and durability improvement, intermittent wet curing methods are better in severe climatic conditions, whereas for shrinkage reduction, neither the dry methods nor intermittent wet curing are suitable techniques.

Sawan [60] compared the results of ordinary Portland cement (OPC) and natural pozzolan (NP) mortars cured under hot and normal conditions by measuring strength and shrinkage. The results showed that OPC mortar specimens gained higher compressive strength than NP mortars, under hot weather conditions. Under hot weather, strength development rate was noted higher in early ages as compared to normally cured mortars. However, the strength of hot weather specimens declined at later ages while strength development of normally cured specimens remained unaffected. Shrinkage results indicated that normally cured OPC samples have higher shrinkage than NP. However, under hot weather, NP specimens showed higher shrinkage values than OPC at early age but later, at the age of one year, all specimens reached about equal values.

Maslehuddin et al. [79] carried out a study to investigate the influence of curing method on plastic and drying shrinkage as well as rate of reinforcement corrosion on plain and silica fume cement concretes. The concrete specimens were cured under wet-burlap or by the application of one of the curing compounds, such as water-, acrylic-, bitumen-based or coal tar epoxy. It was concluded that plastic shrinkage strain in concrete specimens cured by covering with a plastic sheet was more than those cured by applying a curing compound. The concrete specimens cured by bitumen-based curing compound showed minimum plastic shrinkage strain. Also, the drying shrinkage strain in the concrete samples cured under wet burlap was greater than those cured by applying a curing compounds. The least drying shrinkage was recorded in concrete specimen cured by application of coal tar epoxy coating. The authors also reported that 3 days of curing under wet burlap before applying a curing compound was essential for OPC concrete while silica fume cement concrete required 7 days of wet burlap curing from durability perspective.

Al-Gahtani [7] studied the effect of curing conditions by measuring plastic shrinkage, drying shrinkage, compressive strength and pulse velocity of plain and blended cement concretes. The concrete specimens were cast with 100% Type I, 10% very fine fly ash (VFFA), 7% silica fume (SF) and 30% fly ash (FA). The specimens were cured by covering with wet burlap or applying one of the two curing compounds, namely water- and acrylic-based. It was noted that specimen cured by wet burlap achieved more strength than those cured by curing compounds, while minimum plastic and drying shrinkage occurred in compound cured concrete specimens as compared to burlap and plastic sheet curing. Compressive strength and pulse velocity of SF, VFFA and FA cement concretes was greater than that of OPC concrete by any means of curing and these values were, generally, highest in SF cement concrete specimens followed by FA, VFFA and OPC. Plastic shrinkage strain in all blended cement concretes specimens cured by any method was, generally, lower than that in OPC concrete specimens.

Whitting et al. [80] investigated the effect of cracking tendency and drying shrinkage of plain (OPC) and silica fume (SF) cement concretes utilized for bridge decks. It was noted that the capability of concrete to crack was significantly affected by the incorporation of

SF only, when concrete was inadequately cured. At seven days of continuous moist curing of SF cement concrete, the early age cracking was not much affected. Although the long-term shrinkage in both the OPC and SF concretes were approximately identical but at early ages, SF cement concrete exhibited slightly higher shrinkage than OPC concrete. The authors suggested that specifications for the use of SF concretes in bridge deck construction should add a condition for 7-days of moist curing of exposed concretes without interruption.

Al-Gahtani et al. [1] adopted factorial experimental design to investigate the combined effects of: (a) water to cement ratio, (b) total aggregate to cement ratio, (c) fine to total aggregate ratio, and (d) hot weather conditions in terms of concrete mixture temperature (26, 35, 38, 41 or 44°C) at placement and curing conditions (laboratory or field) on workability and compressive strength. The ingredients used in concrete were heated in sun before mixing and suitable quantity of additional water were mixed to compensate the loss of water from the mixture due to evaporation caused by mixing in hot weather condition. It was reported that decreasing the concrete mixture temperature at placement only, as specified in the codes of practice, does not completely alleviate the detrimental effect of hot weather on compressive strength and therefore, it is essential to carry out proper curing of concrete in hot weather. It was observed that compressive strength decreases with increase in casting temperature (T_c) and can be calculated by the following equation:

$$R = (1.30\, T_c - 42.1)\% \;; \qquad \text{for } 35°\text{C} \leq T_c \leq 44°\text{C}$$

Abbasi et al. [81] investigated the influence of hot weather on strength of reinforced concrete beams. They prepared 52 reinforced concrete beams and cured them under hot weather environment at different temperatures. The experimental results indicated that despite the necessary cares are taken during their preparation, the strength of the reinforced concrete beams cast and cured under hot weather could be decreased by approximately 25% when the concrete mixture temperature approaches to about 45°C.

Abbasi and Al-Tayyib [82] studied the effect of hot weather on the flexure and split tensile strength of concrete prepared at different temperatures (between 24 to 45°C) and moist cured under hot weather conditions. The results indicate that the split tensile strength and the modulus of rupture of concrete cast and cured in hot environment are decreased with increase in casting temperature. It was reported that even if the required compressive strength of concrete in hot weather conditions is achieved, the splitting tensile strength and modulus of rupture of concrete could be reduced by 11 and 22%, respectively.

Abbasi and Tayyib [83] presented the experimental results of pulse velocity and modulus of elasticity of concrete cast and cured under various laboratory and hot weather conditions. The normal temperature specimens were cast and cured in laboratory by water ponding or wet burlap, while hot weather specimens were prepared after heating them in oven or in sun to get the concrete mix temperature in the range of 24 to 47°C and then moist- or wet-burlap- cured in the field. The results indicated that due to the adverse effect of atmospheric conditions of hot weather, both the pulse velocity and modulus of elasticity of concrete specimens were significantly decreased with increase in casting temperature of concrete mixture. The authors reported that the modulus of elasticity of concrete specimens could be reduced by approximately 17.5%, even if the concrete mixture is so proportioned as to produce the desired compressive strength for concrete cast and cured under hot weather.

Cebeci [84] studied the influence of concurrently changes in the curing and mixing temperature (17 and 37°C) in conjunction with the relative humidity of the curing media (saturation, 75 and 33%) on strength gain in concrete specimens (up to one year). The results showed that the decrease in humidity of the curing condition, instead of the increase in mix temperature, is the important parameter influencing the strength development. The compressive strength of the concrete specimens placed in low humidity was decreased by 30 to 46% contrast to water cured concrete. Despite this, when all were placed in low humidity, the warm concrete specimens achieved greater strength than the cool ones. Under outdoor curing environment, the result of temperature variation among the specimens cast and placed under direct sunlight and those protected in the shade was not as adverse as the effect of inadequate curing conditions.

Price [85] carried out two sorts of experiments to investigate the effect of temperature at the casting time and during curing, on the strength of concrete. In the first case, concrete was cast and cured at several constant temperatures in the range of 5 to 46°C. The results indicated that concrete cast and cured at higher temperature produced the highest 28-day strength. In the other type of experiment, concrete was cast and placed for two hours at several temperatures in the range of 5 to 46°C and then cured at 21°C for 28-days. Such examination produced completely different result as the concrete cast at higher temperature but cured normally developed the lowest 28-day strength.

Klieger [86] observed a reduction in the concrete strength of about 15% at 41°C as compared to that produced at 23°C. In this research, concrete was made of different kinds of ordinary Portland cement and was mixed, placed and cured at several temperatures in the range of -4 to 49°C. The results showed that strength increased with an increase in the initial curing temperatures for the comparatively early age of 1, 3, and 7 days but decreased at later ages.

Saricimen et al. [87] conducted a study to evaluate the influence of field and laboratory curing on the durability performance of plain and pozzolanic concrete in the Eastern province of Saudi Arabia. The concrete specimens were cast using different types of cements and fly ashes and various mix proportions. The specimens were cured outdoor and in laboratory conditions. By measuring the volume of voids and absorption tests, the permeability of concrete was determined. The authors reported that to produce the least permeable concrete for both the plain and pozzolanic concretes, continuous water curing is better. It was observed that regardless of the curing method adopted, permeability of the fly ash concrete samples were lower than plain cement concretes for an early test age of seven days during curing. The initial surface absorption of laboratory cured fly ash concrete specimens were lower than control concretes after 90 days of curing for all fly ash replacement (10 to 40%) and cement contents (275 to 450 kg/m^3) utilized.

Tan and Gjorv [88] investigated the influence of curing conditions on strength and permeability of plain and silica fume cement concrete. The varying parameters studied were w/c ratios, cement contents, curing temperatures and duration of curing in water and in air. The results indicated that utilizing the silica fume in the mix increases the concrete compressive strength of about 30% but it was noted that silica fume is less sensitive to early drying compared to plain cement concrete. Curing temperature greatly influenced the compressive strength of concrete specimens while resistance to water penetration was not affected by elevated curing temperature. Further, silica fume showed more resistance to water penetration as compared to plain cement concrete.

Austin et al. [58] investigated the effect of strength development and permeability of ordinary Portland cement (OPC) and ground granulated blast furnace slag (GGBFS) concrete exposed in controlled environment where temperature were maintained between 5 and 35°C and relative humidity between 20 and 80%. The effect of curing methods, namely wet burlap, polythene sheets, curing membrane, air curing and water curing were examined. Also, authors investigated the effect of different percentages of GGBFS, specifically 30, 50 and 70% used as cement replacement. In all cases, the GGBFS concrete specimens that were initially cured under wet burlap for 7 days achieved the greater compressive strength and pulse velocity at all test ages up to 28 days than OPC concrete specimens while air cured concrete specimens had lowest strength and pulse velocity. The specimens tested for water absorption and initial surface absorption tests performed best by membrane curing followed by wet burlap, polythene and air curing, in decreasing order. The concrete specimens cast by OPC performed better in temperate climatic conditions, whereas GGBFS concretes were effective in hot weather condition. It was also noted that concrete specimens with 50% cement replacement of GGBFS showed better results in strength and durability with different curing methods.

Shariq et al. [59] carried out experimental investigation to study the effect of ultrasonic pulse velocity on plain and GGBFS (20, 40 or 60% constitution) cement concrete. The

UPV was measured at different ages up to 180 days on prism specimens which were cured in water tank for 28 days and then kept at room temperature until 180 days of testing. The research demonstrated that OPC concrete specimens attained more pulse velocity than GGBFS containing specimens at all percentage level and at all ages. It was noted that 28 day UPV of OPC concrete has been achieved within 90 days by the GGBFS concrete with cement compensation of 20 and 40% but 60% GGBFS concrete did not attained such UPV even in 180 days. The authors established a relationship between compressive strength and UPV which can be utilized to find the strength of concrete for all levels of percentage replacement of GGBFS in concrete and at any age.

Kefeng Tan and Nichols [89] investigated the strength development of concrete at normal and elevated curing temperature. After casting, the normal cured specimens were kept in water tank at 20°C, while the elevated cured specimens were kept in oven at 65°C for 16 h and then placed in same water tank, until testing up to 56 days. The results indicated that under elevated curing, later strength of concrete specimens reduces significantly as compared to normal cured ones. It was also noted that inclusion of blended cements like silica fume, fly ash and blast furnace slag or lowering the w/c ratio mitigate this adverse effect of strength reduction. Among the supplementary cements, silica fume is the most effective means to reduce the later strength reduction. The authors concluded from SEM analysis that it is the uneven distribution of hydration products caused by elevated curing temperature that tends to the reduction in later strength development of concrete.

Al-Amoudi et al. [11] investigated the influence of hot weather on the strength development of plain and blended cement mortars. The specimens were prepared with ordinary Portland cement, 20% fly ash, 10% silica fume, and 70% blast furnace slag with w/cm ratio of 0.3 or 0.4. After casting, the specimens were exposed to 25, 40, 55 and 70°C. The results indicated that the compressive strength at early age increases in both the plain and blended cement mortars cast with w/cm ratio of 0.3 or 0.4, under elevated curing temperature. However, the long-term strength largely depends on w/cm ratio under elevated temperature exposure. The mortar specimens made with w/cm ratio of 0.40 reduced the compressive strength while the behavior of specimens made with w/cm ratio of 0.3 was opposite.

Shoukry et al. [90] investigated the development of mechanical properties of concrete cured under different environmental condition. The temperature was varied from -20 to +50°C and relative humidity between 40 and 60% in an environmental chamber. The results indicated that compressive strength, split tensile strength and modulus of elasticity of concrete were degraded by higher temperature and humidity and were inversely related to environmental conditions.

Al-Amoudi [19] reported that the concrete permeability is significantly reduced for a w/c ratio below 0.45. The author suggested that the w/c ratio should be less than 0.45, and preferably around 0.40, to obtain good durability of concrete in normal exposure conditions. However, suitable dosage of admixtures may be added to obtain the desired workability at this w/c ratio. Further, ACI 318 and BS 8110 have imposed similar limits on the concrete structures exposed to aggressive environments.

Al-Amoudi et al. [91] developed correlation among compressive strength and some durability indices. In this research, compressive strength, water permeability and chloride diffusion coefficient after 28 days of moist curing were tested on plain, 7.5% silica fume

(SF) or 20% fly ash (FA) cement concrete samples prepared for a range of cementitious materials content (300, 350 or 400 kg/m^3) and water to binder ratio (0.35, 0.40, 0.45 or 0.5 by mass). The compressive strength of all types of cementing materials were decreased with increase in w/cm ratio. The highest and lowest compressive strength was observed, respectively in SF and FA cement concrete specimens after 28-day moist curing. It was noted that the depth of water penetration also increased with increasing w/cm ratio. At same w/cm ratio and cementitious materials content, the lowest and highest depth of water penetration was measured in SF and OPC concretes, respectively. Both compressive strength and water permeability improved with increase in cementitious material content.

Demirboga et al. [92] developed a relationship among ultrasonic pulse velocity and compressive strength for mineral admixture concrete. They performed ultrasound test to evaluate the compressive strength of concretes. The cementing materials used were 100% ordinary Portland cement (OPC), while Fly ash (FA) and blast furnace slag (BFS) replacement were 50, 60 or 70%. All concrete specimens were prepared with same w/cm ratio of 0.35 and moist cured up to 120 days. The results showed that at an early age of curing, both UPV and compressive strength at all levels of blended cement concretes were very low as compared to OPC concrete. However, with increase in curing period, both properties of concrete increased. It was also noted that concrete specimens with 50% replacement of FA and BFS performed best and compressive and UPV values reduced with increase in level of replacement. Moreover, BFS concrete specimens attained more strength and pulse velocity than FA concretes at all test ages. The authors also reported that the relationship between UPV and compressive strength was exponential for both FA and BFS concretes.

Elsayed [93] experimentally studied the influence of mineral admixture on water permeability and compressive strength of concrete. The variable parameters studied were 100% ordinary Portland cement (OPC) and replacement of blended cement in OPC was 50% ground granulated blast furnace slag (GGBFS); 5, 10 or 15% of silica fume (SF) and fly ash (FA); while Superpozz (SP) was 10, 20 or 30%. The cube specimens were cast with w/cm ratio of 0.4 and tested at the age of 28-day. The results indicated that with increase in cement replacement level in FA and SP concrete, the concrete properties decreases. The optimum replacement at which SF, FA and SP concrete performed best was 10, 20 and 10%, respectively which resulted in high compressive strength and low water penetration. It was noted that highest compressive strength was given by SF concretes followed by GGBFS, SP, OPC and then FA. However, water penetration depth in SF, SP and FA concrete were significantly lower than GGBFS and OPC concrete.

Najimi et al. [94] investigated the effect of natural pozzolan on Portland cement. Concrete mixtures with 25% replacement of cement with natural pozzolan were studied. The blended and control mixes were tested for mechanical and durability properties. Compressive strength of specimens after 180 days was slightly decreased (i.e. less than 5%). The specimens with pozzolan had slightly enhanced the modulus of elasticity and decreased chloride ion permeability, but did not perform well in freeze and thaw and sulphate expansion tests when compared to control specimen. Due to the lower content of amorphous silica in natural pozzolan, it was also found that the hydration rate was slow. Therefore, the best properties were obtained after 90 and 180 days of curing.

The review of literature, cited above, disclosed that most of the studies conducted so far concentrated on the effect of hot weather on the mechanical properties, especially the compressive strength. Few studies have been conducted on the effect of hot weather on plastic and drying shrinkage cracking. However, none of the studies have concentrated on the effect of hot weather on the durability of concrete. Further, the performance of blended cement concretes prepared with supplementary cementing materials, such as fly ash, silica fume, blast furnace slag, etc., has not been very well addressed.

With the increased usage of blended cement concrete and different curing practices throughout the world including the Arabian Gulf, the effect of hot weather conditions on their strength, shrinkage, and durability characteristics needs to be studied in order to minimize damage due to hot weather and update the prevailing codes of practices.

CHAPTER 3

RESEARCH METHODOLOGY

This research focused on the evaluation of the effect of casting temperature and curing regime on the mechanical properties, durability and shrinkage characteristics of plain and blended cement concretes (such as fly ash, Superpozz, silica fume, blast furnace slag and natural pozzolan). Plain and blended cement concrete specimens were cast at various temperatures (25, 32, 38 or 45°C) normally experienced in the Arabian Gulf and cured by the application of a curing compound, covering with wet burlap and water ponding. To achieve the objective of this proposed work, the following phases were followed. First phase was to procure the concrete ingredients and the necessary equipment from abroad and/or from local suppliers in Saudi Arabia. In the second phase, preparation and curing of specimens were carried out and in the third phase, testing of specimens was done to ascertain the mechanical, shrinkage and durability properties. In this chapter, all these three phases were discussed thoroughly. The data developed in this study were utilized to recommend optimum casting temperature and beneficial curing regime for plain and blended cement concretes.

3.1 Materials

3.1.1 Cementitious Materials

Ordinary Portland cement (OPC) conforming to ASTM C 150 Type I with a specific gravity of 3.15 was used alone as well as in all the concrete mixtures. For blended cement concretes, 10% Superpozz® or very fine fly ash (VFFA), 30% fly ash (FA), 7% silica fume (SF), 70% ground granulated blast furnace slag (GGBFS) and 20% natural pozzolan (NP) were used as replacements of Portland cement. Table 3.1 shows the chemical composition of the Portland cement and blending materials.

Table 3.1: Chemical Composition of Type I and Blending Materials.

Constituent Weight (%)	**OPC**	**VFFA**	**FA**	**SF**	**GGBFS**	**NP**
CaO	64.35	4.4	10.0	0.48	44.0	7.44
SiO_2	22	53.5	52.3	92.5	27.7	40.23
Al_2O_3	5.64	34.3	25.2	0.72	12.8	14.51
Fe_2O_3	3.8	3.6	4.6	0.96	1.20	17.98
K_2O	0.36	-	0.10	0.84	0.10	0.89
MgO	2.11	1.0	2.20	1.78	8.80	8.3
Na_2O	0.19	-	0.10	0.5	0.40	3.6
Equivalent alkalis ($Na_2O + 0.658K_2O$)	0.42	-	-	-	-	-
Loss on ignition	0.7	-	-	1.55	-	1.6
C_3S	55	-	-	-	-	-
C_2S	19	-	-	-	-	-
C_3A	10	-	-	-	-	-
C_4AF	7	-	-	-	-	-

3.1.2 Aggregates

The coarse aggregates and sand used in this study were taken from local quarries. The coarse aggregates used were crushed limestone procured from Riyadh Road region. The fine aggregate was dune sand. The specific gravity and absorption of the coarse and fine aggregates are shown in Table 3.2. The grading of coarse aggregates was selected conforming to ASTM C 33 (Size No. 57) is shown in Table 3.3. However, the coarse to fine aggregate ratio of 1.8 by mass kept constant in all the mixtures. Further, potable water was used for casting and curing all the concrete specimens.

Table 3.2: Absorption and Specific Gravity of the Coarse and Fine Aggregates.

Aggregate	Absorption (%)	Bulk Specific Gravity
Coarse Aggregate	1.1	2.6
Fine Aggregate	0.6	2.56

Table 3.3: Grading of Coarse Aggregates.

Size (mm)	% Retained	Cumulative % Retained	Cumulative % Passing	ASTM C 33 (No. 57 Size)
19	0	0	100	100
12.5	70	70	30	25 – 60
4.75	25	95	5	0 – 10
2.36	5	100	0	0 – 5

Note: For the preparation of slab and prism specimens (having some narrow dimensions), aggregate size of 4.75 and 2.36 mm were used 70 and 30%, respectively, which satisfied the recommendations of ACI Committee 318 and ASTM C 33 regarding maximum size of coarse aggregate and grading of aggregate, respectively.

3.1.3 Superplasticizer

Varying dosage of superplasticizer (Sikament® NN, which complies with ASTM C 494, Type F) was used to obtain a slump of 100 ± 25 mm for all the mixtures, after conducting trial mixes in the field conditions.

3.2 Concrete Mixture Variables

Two series of concrete specimens were prepared as detailed below:

Series I: Plain Cement Concrete

- Cement: ASTM C 150 Type I
- Water to cement (w/c) ratio: 0.3, 0.4 and 0.45 (by mass)
- Cement content: 350 kg/m^3

Series II: Blended Cement Concrete

- Cementitious material: ASTM C 618 fly ash (30%), very fine fly ash (10%), silica fume (7%), blast furnace slag (70%) and natural pozzolan (20%), by weight of cement
- Water to cementitious materials (w/cm) ratio: 0.40 (by mass)
- Cementitious materials content: 350 kg/m^3

3.3 Casting Temperature

The concrete mixtures were cast at each of the following temperatures based on the range of ambient temperatures recorded in Saudi Arabia and taken into account the limit of fresh concrete temperatures specified by the local and international codes:

i. 25°C
ii. 32°C
iii. 38°C
iv. 45°C.

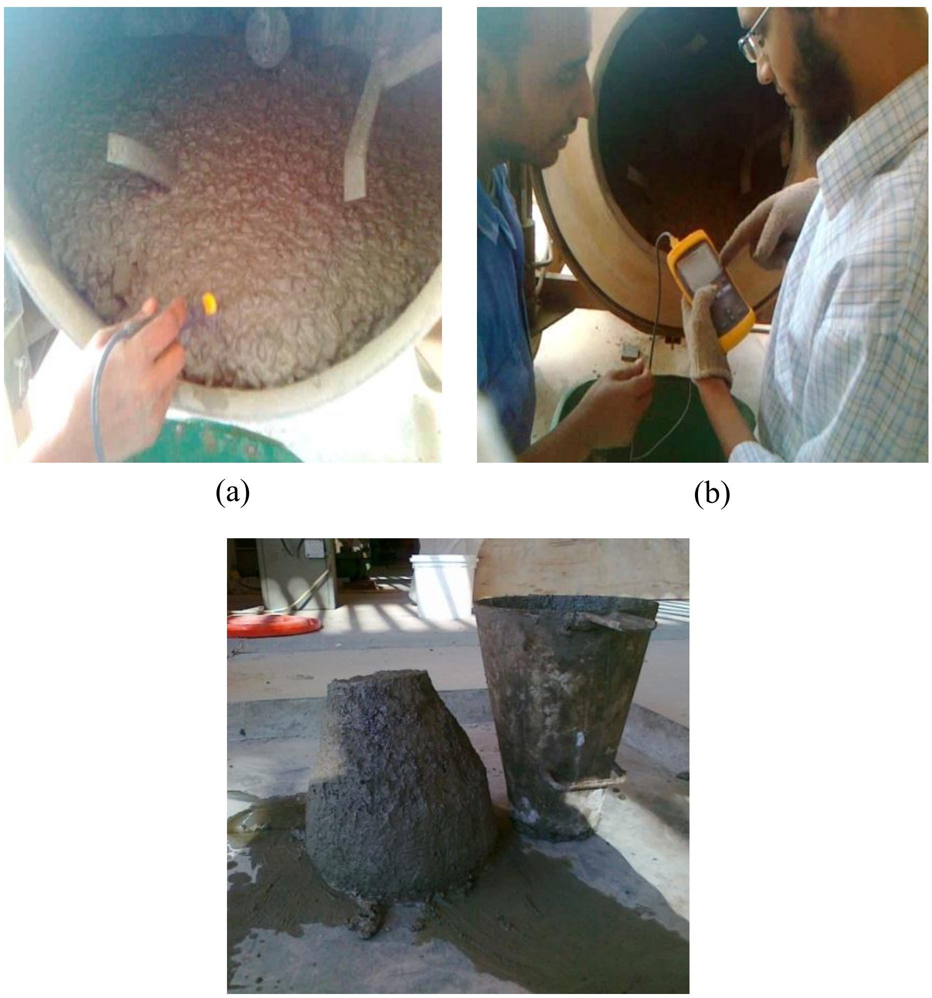
3.4 Preparation of Concrete Specimens

The concrete mixtures were prepared outside the laboratory in hot weather. Based on the results of several trial mixes; to achieve the required mix temperature of 25 and 32°C, varying amount of crushed ice was used in mixing water and ensured that all ice had melted at the time of mixing while to target the mix temperature of 38 and 45°C, the aggregates and sand were pre-heated in the sun before casting for different durations and/or boiled water was used. For fair comparisons of the properties of fresh and hardened concrete, due to the variation in environmental conditions, all concrete mixes were cast during the summer between 9:00 am to 12:00 noon.

A total of 32 concrete mixtures were prepared. The volume of each mix was about 0.168 m^3. The concrete constituents were weighed in required proportions and mixed in an electrically rotating drum type concrete mixer of 1.7 m^3 capacity in accordance with ASTM C 192.

The ingredients were put in the mixer in the following sequence: First the aggregates and sand were placed in the mixer then cement and/or supplementary cementing materials were added. The superplasticizer was added to the mix water and thoroughly stirred to a uniform colour. Some amount of mixing water was added and mixing continued for about 3 min. Thereafter, the remaining mixing water was added and mixing continued for another 5 to 8 min until the mix became uniform. After mixing, the temperature of the concrete mixture was recorded by placing a digital thermometer (accuracy of ± 0.3°C). For all the mixes, the average ambient temperature was about 38°C at the time of casting while the minimum and maximum temperature recorded were 35 and 42°C, respectively.

Further, the slump was measured in accordance with the provisions of ASTM C 143 and then the mix was poured in the molds in two layers and concrete was consolidated using a table vibrator till a thin sheen formed a water layer that appeared on the surface of the specimen, to eliminate the entrapped air. The concrete surface was levelled in one direction by trowel. After finishing, concrete specimens were placed in the ambient summer conditions for 24 hours by covering with a plastic sheet. Figure 3.1 shows measurement of concrete mix temperature and conducting slump test prior to casting.



(a) (b)

(c)

Figure 3.1: Preparation of Specimens: (a), (b) Recording Concrete Casting Temperature and (c) Slump Measurement.

3.5 Curing

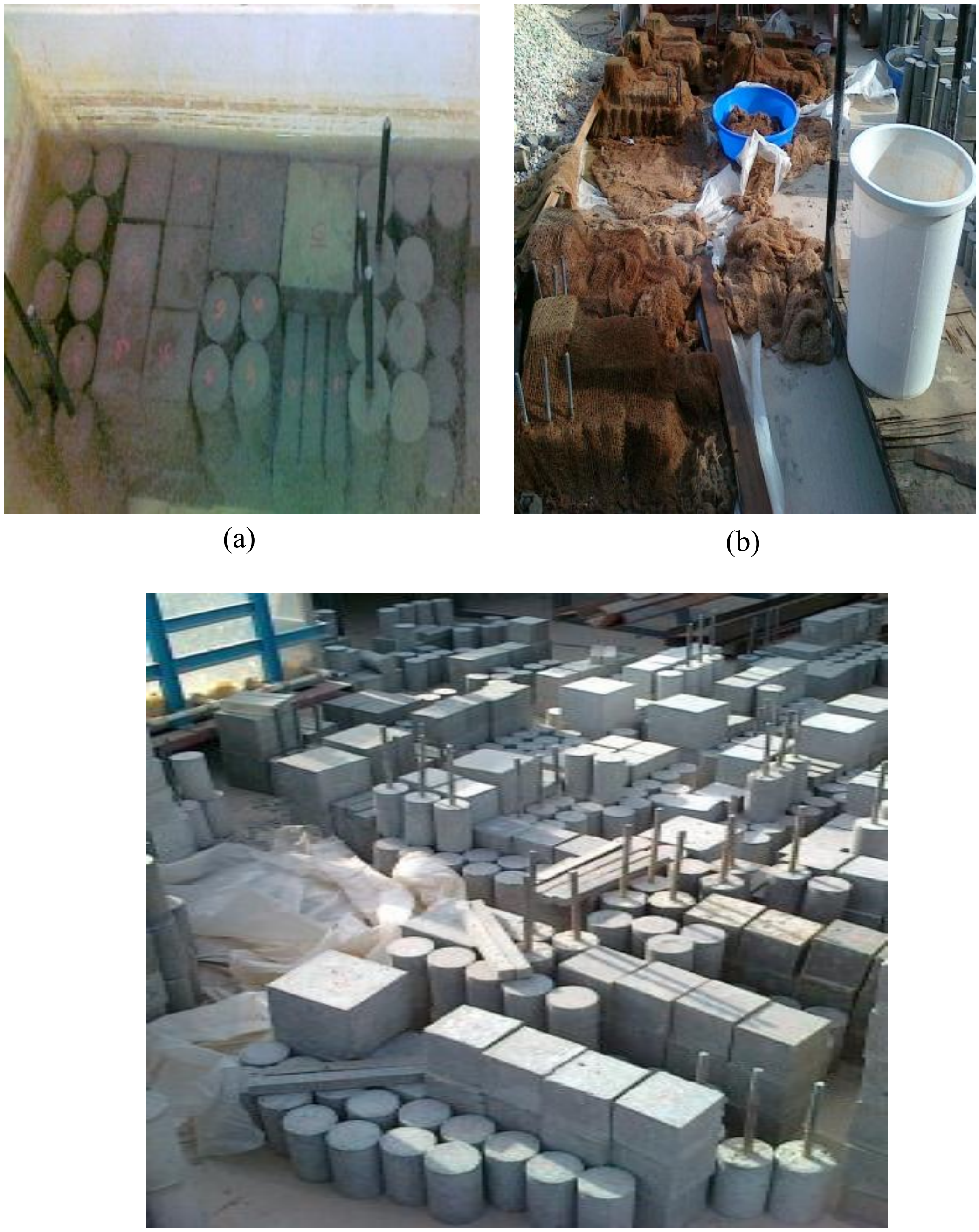
After 24 hours of curing in the molds in "open" atmosphere, the concrete specimens were demolded and categorized into three groups under the following three curing conditions:

i. Submerged in the saturated calcium hydroxide solution under the laboratory environment (22 ± 3°C). This type of curing was considered as the "Reference" curing regime in order to assess the impact of hot weather conditions on the various parameters to be investigated in this study.

ii. Covered with wet burlap. This "Standard" type of curing represents the normal practice by the construction industry whereby the concrete was covered with burlap wetted by water twice daily, in the open atmosphere.

iii. Applying a selected curing compound. This "Special" type of curing is nowadays practiced in several remote projects due to the scarcity of water. In this study, the curing compound used was Antisol®-E10 (a liquid, paraffin based) and applied to newly laid concrete surfaces after ½ hour of casting and applied to all surfaces after demoulding using hand spray gun with a coverage rate of about 0.16 - 0.19 kg/m^3, as per the manufacturer's requirements. Thereafter, the concrete specimens were remained place in the open atmosphere till the time of testing.

The submerged and burlap covered specimens were taken out after 14 days of curing and then they were remained place in the laboratory and field conditions, respectively. After the specified curing period, the required number of concrete specimens were collected from the above three curing regimes in order to prepare them for the testing program. Figure 3.2 shows concrete specimens placed under the three curing regimes.



(a) (b)

(c)

Figure 3.2: Exposure of Concrete Specimens under Three Curing Regimes: (a) Water Ponding in Lab, (b) Covering with Wet Burlap in Field and (c) Applying Curing Compound in Field.

3.6 Evaluation of Properties

The effect of casting temperature, curing regime and/or w/c ratio on plain and blended cement concrete were assessed by the following properties of concrete:

i. Compressive strength;
ii. Split tensile strength;
iii. Pulse velocity;
iv. Depth of water penetration;
v. Plastic shrinkage strain; and
vi. Drying shrinkage strain.

The summary of the experimental program is shown by a flow chart in Figure 3.3.

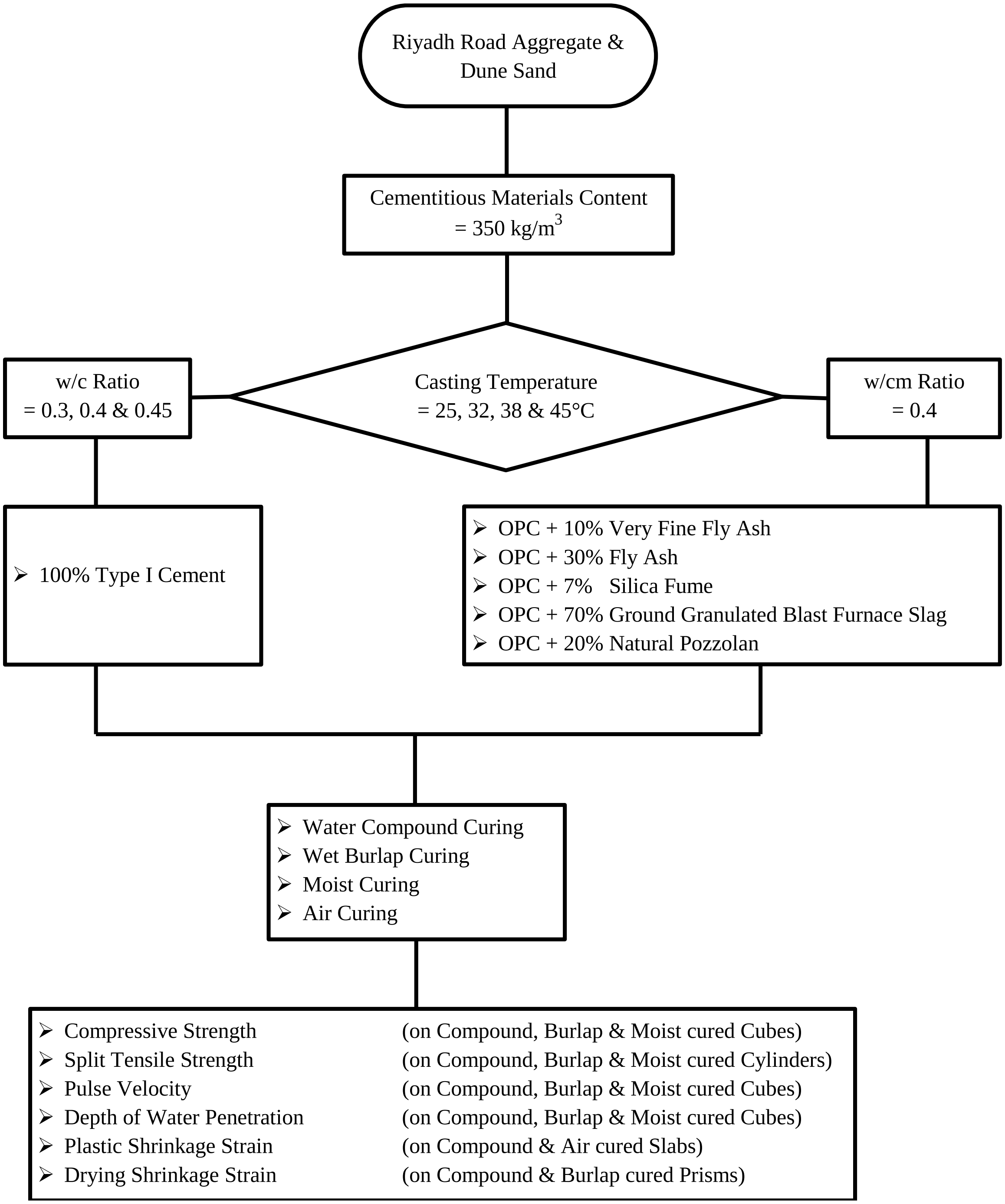


Figure 3.3: Flow Chart of the Experimental Program.

Details of the test properties, testing procedures, specimen type and size and testing durations are summarized in the following table:

Table 3.4: Detail of the Experimental Program.

Property	Procedure	Specimen Size	Test Duration	No. of Specimens
Compressive strength	ASTM C 39	100 mm Cube	3, 7, 28, 90 and 180 days	9 x 5 x 32 = 1440
Split tensile strength	ASTM C 496	75 mm diameter and 150 mm high Cylinder	3, 7, 28, 90 and 180 days	9 x 5 x 32 = 1440
Pulse velocity	ASTM C 597	100 mm Cube	3, 7, 28, 90 and 180 days	Tested on Compressive strength samples
Depth of water penetration	DIN 1048	150 mm Cube	28 days	9 x 32 = 288
Plastic shrinkage strain	Non-standard procedure	500 x 500 x 25 mm Slab	Immediately after casting for 24 hrs.	2 x 32 = 64
Drying shrinkage strain	ASTM C 157	25 x 25 x 275 mm Prism	3, 10, 38, 73, 101, 129 and 185 days	6 x 32 = 192
				Total = 3424

3.6.1 Compressive Strength

Compressive strength of a material is that value of the uniaxial compressive stress reached when the material fails completely. Strength test results of cubes can be used for controlling the quality of structural elements. Compressive strength was calculated from the failure load divided by the cross-sectional area resisting the load and specified in mega Pascals (MPa). Compressive strength was determined on the same 100 mm cube specimens after performing pulse velocity according to ASTM C 39 [95] using a digital compression testing machine (MATEST, having 3000 kN capacity) at 3, 7, 28, 90 and 180 days of curing. In each mix, three samples from each curing regimes were tested for compressive strength and averages of the three values are reported. Figure 3.4 shows the compression testing machine (MATEST) with cube specimen.

(a) (b)

Figure 3.4: Compressive Strength Setup: (a) Compression Testing Machine and (b) Close-up View of a Typical Cube.

3.6.2 Split Tensile Strength

As concrete is weak in tension, determination of tensile strength of concrete is essential for determining the load at which concrete members may crack. Due to ease, accuracy and greater factor of safety of indirect method, such as split tensile strength for measuring tensile strength of concrete, is preferred on direct tests. This test consists of applying a compressive line load along the horizontal axis of the cylinder at a rate within the prescribed range until failure occurs. From failure load, split tensile strength is calculated by following formula:

$$T = 2P / \pi l d$$

Split tensile strength was determined on 75 mm diameter and 150 mm high cylindrical specimens in accordance with ASTM C 496 using a compression testing machine, having 700 kN capacity, at 3, 7, 28, 90 and 180 days of curing. In each mix, three samples from three curing regimes were tested for split tensile strength and averages of the three values were reported. Figure 3.5 shows the compression testing machine with a cylindrical specimen.

(a) (b)

Figure 3.5: Split Tensile Strength Setup: (a) Compression Testing Machine and (b) Close-up View of a Typical Cylinder.

3.6.3 Pulse Velocity

A non-destructive, ultrasonic pulse velocity technique is often used to assess the general quality and relative denseness of in-situ concrete structures. Researchers [105,106] have suggested a general classification of the quality of concrete on the basis of the pulse velocity values, for concretes having density of about 2400 kg/m^3, as follows:

Pulse Velocity (m/s)	Quality
4500 and above	Excellent
3500 - 4500	Good
3000 - 3500	Fair
2000 – 3000	Poor
2000 and below	Very Poor

Pulse velocity of concrete samples was determined using the TICO pulse velocity equipment, as shown in Figure 3.6. This equipment essentially consists of a transducer, which propagates an ultrasonic pulse through the concrete to be received by a receiving transducer. The instrument displays the time taken by the wave to travel the measured path of concrete. The path length divided by travel time gives the pulse velocity. Transducers of 54 kHz frequencies were used in this test. The pulse velocity was measured on 100 mm cube concrete specimens that were later tested for compressive strength at 3, 7, 28, 90 and 180 days of curing. In each mix, three samples from three curing regimes were tested for pulse velocity and averages of the three values were reported. The moist cured and burlap cured specimens were allowed to dry in the laboratory environment for few hours at 3 and 7 days of testing, the instrument was checked with calibration rod and contact between transducers and concrete specimens were made using grease, prior to testing for pulse velocity according to ASTM C 597.

(a) (b)

Figure 3.6: Pulse Velocity Setup: (a) Pulse Velocity Equipment and (b) Typical Cube Specimens.

3.6.4 Depth of Water Penetration

The permeability of concrete is commonly determined by the water permeability test, specified by DIN 1048. Generally, concrete quality can be assessed from its depth of water penetration according to the Concrete Society as [98]:

Depth of Water Penetration (mm)	Permeability
< 30	Low
30 to 60	Moderate
> 60	High

In this test, 150 mm concrete cube specimens were taken out after 28 days of the field and lab curing. The specimens were allowed to cool for 1 day in the laboratory conditions before putting into the test chamber. Using air compressor, a constant water pressure of five bars was applied on one face of the specimen for a period of 72 hrs. Thereafter, specimens were taken out and split open into two halves with the help of the compression testing machine. The profile of water penetrated in the concrete was then marked and the maximum depth of water penetration was recorded. The average reading of three specimens was considered as an indicator of the water permeability in each curing regime. Figure 3.7 shows the set-up used to determine the depth of water penetration in this study.

(a)

(b)

Figure 3.7: Water Permeability Setup: (a) Test Chamber and (b) Permeability Profile on a Typical Cube Specimen after Splitting.

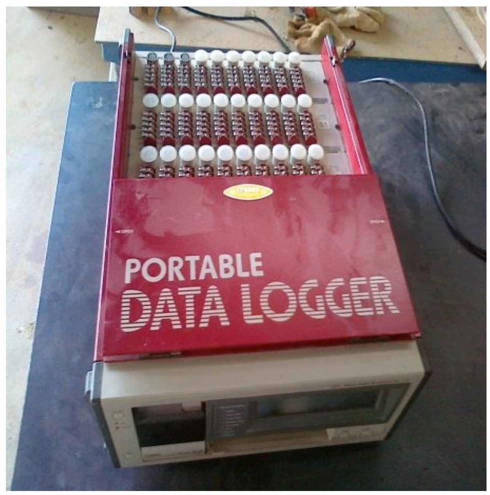
3.6.5 Plastic Shrinkage Strain

Shrinkage is an important property of fresh concrete that depends on the environmental conditions. Plastic shrinkage cracks appear mostly on the horizontal surface of fresh concrete after placing and finishing due to rapid loss of water by evaporation and are usually parallel to each other. These cracks are necessary to control to avoid reduction in strength and durability of concrete.

After casting and finishing, concrete slabs were placed in the ambient summer conditions. During this time, plastic shrinkage measurements were conducted on the plexi-glass slab specimens [73] of size 500 x 500 x 25 mm. Two slab specimens were prepared in each mix and were cured by the application of curing compound and air cured. Plastic shrinkage strains were recorded by embedding aluminum studs measuring 25 x 6 x 150 mm to a depth of 10 mm in the slab specimens. The strips were placed at about 50 mm from the edge of the mid-section of each of the four sides of the specimen. The movement of the studs were monitored through four linear variable differential transducers (LVDTs) that were connected to a data acquisition system. Although plastic shrinkage occurs within about the first 6 hrs. after casting, full range of values were taken for a period of 24 hrs. Shrinkage displacement readings were continuously recorded at the interval of every 10 min for first 6 hrs. and every 30 min thereafter. The schematic view of the experimental setup is shown in Elsevier [48,76,79]. Figure 3.8 shows a typical slab specimens with LVDTs and data logger for measuring the plastic shrinkage strain.

(a)

(b)



(c)

Figure 3.8: Plastic Shrinkage Setup: (a) Typical Slab Specimen with LVDTs, (b) Close-up View of a LVDT and (c) Data Logger.

3.6.6 Drying Shrinkage Strain

After curing the prism specimens for 14 days in the field (by covering with wet burlap or applying a curing compound), samples from all the curing regimes were transferred to high temperature laboratory for drying shrinkage testing and further exposure. The shrinkage displacements were recorded by comparing it with the length of a reference steel prism. The change in length of the concrete prisms was monitored through linear variable differential transducer (LVDT) that was connected to a data acquisition system.

After taking initial reading, drying shrinkage strains were measured at the ages of 3, 10, 38, 73, 101, 129 and 185 days. In each mix, three samples from two curing regimes were tested for drying shrinkage and averages of the three values were reported in accordance with ASTM C 157 [99]. A set of shrinkage specimens with measuring setup is shown in Figure 3.9.

(a) (b)

Figure 3.9: Drying Shrinkage Setup: (a) Frame with LVDT and Data Logger and (b) Typical Prism Specimens.

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CHAPTER 4

RESULTS AND DISCUSSION

In this Chapter, the results of the experimental work conducted to evaluate the effect of casting temperature and curing conditions on the mechanical properties, durability and shrinkage characteristics of plain and blended cement concretes were discussed. As stated in Chapter 3 the effect of following individual and cumulative parameters on the properties of plain and blended cement concretes were evaluated:

- **w/c ratio:** 0.3, 0.4 or 0.45.
- **Casting temperature:** 25, 32, 38 or 45°C.
- **Curing regime:** Moist curing, wet burlap curing, application of curing compound or air curing.
- **Cementitious materials:** Ordinary Portland cement (OPC) or partial replacement in OPC by pozzolanic materials, such as 10% very fine fly ash (VFFA), 30% fly ash (FA), 7% silica fume (SF), 70% ground granulated blast furnace slag (GGBFS) or 20% natural pozzolan (NP).

The test results are presented and discussed in the following sections.

4.1 Compressive Strength

The average compressive strength of OPC and blended cement concrete specimens, prepared with a w/cm ratio of 0.3, 0.4 or 0.45, cast at 25, 32, 38 or 45°C and tested after 3, 7, 28, 90 and 180 days of curing under moist condition, covering with wet burlap or applying a curing compound is summarized in Tables 4.1 through 4.3. Further, the data presented in Table 4.4 show the compressive strength development of all types of concretes expressed as a fraction of the 28-day strength. Moreover, quantitative analysis of the compressive strength of all kinds of concretes were carried out as shown in Table 4.5, where the compressive strength of each cementitious materials is expressed as a fraction of the corresponding strength of OPC concrete.

Table 4.1: Compressive Strength of OPC and Blended Cement Concretes Cured by Water Ponding.

Mix No.	Cementitious Materials	w/c Ratio	Casting Temp. (°C)	Compressive Strength (MPa)				
				3 Days	7 Days	28 Days	90 Days	180 Days
1	100% OPC	0.3	25	28.2	33.5	47.8	58.3	62.6
2	100% OPC	0.3	32	30.4	34.7	54.4	65.8	69.8
3	100% OPC	0.3	38	33.2	36.6	52.1	63.5	67.6
4	100% OPC	0.3	45	34.7	38.6	46.5	56.9	59.3
5	100% OPC	0.4	25	23.5	27.2	40.0	51.6	56.2
6	100% OPC	0.4	32	24.6	28.1	47.1	59.3	63.5
7	100% OPC	0.4	38	26.8	30.2	43.4	55.2	59.1
8	100% OPC	0.4	45	28.5	33.3	39.6	48.6	54.4
9	100% OPC	0.45	25	18.1	23.3	36.5	48.2	52.0
10	100% OPC	0.45	32	19.0	23.7	41.7	53.8	58.8
11	100% OPC	0.45	38	21.2	25.4	38.6	52.0	56.4
12	100% OPC	0.45	45	23.6	28.1	35.9	46.4	49.6
13	OPC + 10% VFFA	0.4	25	21.9	25.4	43.0	54.1	60.3
14	OPC + 10% VFFA	0.4	32	26.6	29.2	47.4	61.2	66.6
15	OPC + 10% VFFA	0.4	38	27.1	29.5	48.2	62.9	69.7
16	OPC + 10% VFFA	0.4	45	27.9	31.6	45.3	57.6	63.4
17	OPC + 30% FA	0.4	25	20.4	24.7	38.2	52.0	58.5
18	OPC + 30% FA	0.4	32	20.7	25.0	45.1	61.9	68.3
19	OPC + 30% FA	0.4	38	22.3	26.5	47.4	63.6	70.3
20	OPC + 30% FA	0.4	45	24.8	27.6	37.8	50.2	57.6
21	OPC + 7% SF	0.4	25	26.4	29.9	44.2	56.1	62.0
22	OPC + 7% SF	0.4	32	28.0	31.5	50.4	64.1	70.3
23	OPC + 7% SF	0.4	38	29.3	34.1	48.6	61.4	67.0
24	OPC + 7% SF	0.4	45	31.5	35.7	43.4	54.2	60.6
25	OPC + 70% GGBFS	0.4	25	16.2	19.8	31.3	45.6	50.4
26	OPC + 70% GGBFS	0.4	32	17.5	21.1	34.6	51.4	57.1
27	OPC + 70% GGBFS	0.4	38	18.8	22.4	38.3	56.0	61.3
28	OPC + 70% GGBFS	0.4	45	20.5	24.2	30.4	43.8	50.0
29	OPC + 20% NP	0.4	25	18.8	22.9	35.2	47.4	52.1
30	OPC + 20% NP	0.4	32	22.0	24.6	39.9	52.7	58.4
31	OPC + 20% NP	0.4	38	22.5	25.2	40.6	56.4	62.2
32	OPC + 20% NP	0.4	45	23.2	26.8	37.6	51.4	59.0

Table 4.2: Compressive Strength of OPC and Blended Cement Concretes Cured by Covering with Wet Burlap.

Mix No.	Cementitious Materials	w/c Ratio	Casting Temp. (°C)	Compressive Strength (MPa)				
				3 Days	7 Days	28 Days	90 Days	180 Days
1	100% OPC	0.3	25	26.0	31.1	43.6	50.9	55.4
2	100% OPC	0.3	32	26.2	31.5	49.5	62.4	66.3
3	100% OPC	0.3	38	27.5	33.8	47.2	59.3	62.7
4	100% OPC	0.3	45	29.6	35.1	42.4	50.3	54.1
5	100% OPC	0.4	25	20.5	24.3	36.4	45.5	48.7
6	100% OPC	0.4	32	23.1	26.1	42.2	54.4	57.9
7	100% OPC	0.4	38	24.6	28.1	38.8	50.9	54.4
8	100% OPC	0.4	45	25.4	30.7	35.3	42.3	47.5
9	100% OPC	0.45	25	17.0	21.5	32.9	41.4	45.1
10	100% OPC	0.45	32	18.2	22.5	38.5	50.4	52.9
11	100% OPC	0.45	38	19.7	24.5	36.2	47.5	50.8
12	100% OPC	0.45	45	21.9	26.4	31.7	39.1	44.3
13	OPC + 10% VFFA	0.4	25	17.4	21.2	38.5	48.6	52.1
14	OPC + 10% VFFA	0.4	32	24.5	27.7	43.6	55.2	62.4
15	OPC + 10% VFFA	0.4	38	25.2	27.9	44.3	58.0	63.9
16	OPC + 10% VFFA	0.4	45	26.3	29.4	42.5	53.0	58.2
17	OPC + 30% FA	0.4	25	16.6	20.5	35.4	46.7	50.8
18	OPC + 30% FA	0.4	32	17.9	22.6	41.6	56.3	63.2
19	OPC + 30% FA	0.4	38	20.2	25.4	43.8	58.2	65.1
20	OPC + 30% FA	0.4	45	22.5	26.1	34.4	46.0	51.9
21	OPC + 7% SF	0.4	25	24.1	27.6	40.3	50.8	57.3
22	OPC + 7% SF	0.4	32	25.8	29.2	47.0	59.3	65.5
23	OPC + 7% SF	0.4	38	27.2	32.0	44.8	57.1	63.0
24	OPC + 7% SF	0.4	45	29.3	34.2	40.1	48.8	55.4
25	OPC + 70% GGBFS	0.4	25	14.0	17.7	29.2	41.8	46.3
26	OPC + 70% GGBFS	0.4	32	16.2	19.4	31.8	46.3	52.2
27	OPC + 70% GGBFS	0.4	38	17.1	21.5	36.4	52.6	56.5
28	OPC + 70% GGBFS	0.4	45	19.3	22.6	27.1	39.8	43.4
29	OPC + 20% NP	0.4	25	17.1	20.4	33.6	45.3	49.7
30	OPC + 20% NP	0.4	32	19.4	22.8	36.5	49.1	54.7
31	OPC + 20% NP	0.4	38	20.2	23.5	40.0	53.6	59.2
32	OPC + 20% NP	0.4	45	21.5	24.7	34.8	47.8	53.4

Table 4.3: Compressive Strength of OPC and Blended Cement Concretes Cured by Applying a Curing Compound.

Mix No.	Cementitious Materials	w/c Ratio	Casting Temp. (°C)	Compressive Strength (MPa)				
				3 Days	7 Days	28 Days	90 Days	180 Days
1	100% OPC	0.3	25	23.9	27.3	40.3	49.7	53.2
2	100% OPC	0.3	32	24.8	29.2	46.7	60.2	63.4
3	100% OPC	0.3	38	26.4	31.7	44.4	56.9	59.5
4	100% OPC	0.3	45	28.6	33.4	39.7	47.3	51.6
5	100% OPC	0.4	25	19.9	22.8	34.2	41.8	45.3
6	100% OPC	0.4	32	21.5	24.0	40.7	52.7	55.2
7	100% OPC	0.4	38	22.9	26.4	37.7	48.6	51.9
8	100% OPC	0.4	45	24.2	28.0	32.5	41.5	43.1
9	100% OPC	0.45	25	13.7	18.6	29.8	39.7	42.2
10	100% OPC	0.45	32	15.5	20.2	36.9	48.1	50.3
11	100% OPC	0.45	38	19.4	23.1	34.8	45.3	48.8
12	100% OPC	0.45	45	19.8	24.3	29.4	37.9	41.5
13	OPC + 10% VFFA	0.4	25	15.6	20.3	36.8	45.9	49.5
14	OPC + 10% VFFA	0.4	32	21.4	24.8	41.1	53.0	59.8
15	OPC + 10% VFFA	0.4	38	22.7	25.4	42.5	55.3	62.0
16	OPC + 10% VFFA	0.4	45	23.6	27.1	39.2	50.1	53.7
17	OPC + 30% FA	0.4	25	14.1	18.0	32.3	44.6	47.9
18	OPC + 30% FA	0.4	32	16.5	20.8	38.9	54.5	60.7
19	OPC + 30% FA	0.4	38	18.7	22.6	41.2	55.9	63.3
20	OPC + 30% FA	0.4	45	20.0	24.3	31.6	43.4	47.2
21	OPC + 7% SF	0.4	25	22.7	25.5	38.8	48.4	53.9
22	OPC + 7% SF	0.4	32	23.6	26.4	44.5	56.7	63.1
23	OPC + 7% SF	0.4	38	25.5	29.4	43.6	53.9	60.7
24	OPC + 7% SF	0.4	45	26.8	31.8	36.2	45.5	51.7
25	OPC + 70% GGBFS	0.4	25	11.8	14.6	25.9	37.5	41.9
26	OPC + 70% GGBFS	0.4	32	13.5	15.7	28.5	42.8	47.6
27	OPC + 70% GGBFS	0.4	38	15.2	17.9	33.7	49.2	52.8
28	OPC + 70% GGBFS	0.4	45	17.1	20.8	23.6	35.5	39.7
29	OPC + 20% NP	0.4	25	14.7	18.5	30.3	41.6	44.5
30	OPC + 20% NP	0.4	32	17.2	19.2	34.3	46.5	50.3
31	OPC + 20% NP	0.4	38	18.6	21.0	36.9	50.8	55.1
32	OPC + 20% NP	0.4	45	19.3	22.6	32.4	45.0	50.3

Table 4.4: Compressive Strength of OPC and Blended Cement Concretes Compared to 28-day Strength - Average of all Curing Regimes.

Mix No.	Cementitious Materials	w/c Ratio	Casting Temp. (°C)	f_c / f_c (28 Days)				
				3 Days	7 Days	28 Days	90 Days	180 Days
1	100% OPC	0.3	25	0.59	0.70	1.00	1.21	1.30
2	100% OPC	0.3	32	0.54	0.63	1.00	1.25	1.33
3	100% OPC	0.3	38	0.60	0.71	1.00	1.25	1.32
4	100% OPC	0.3	45	0.72	0.83	1.00	1.20	1.28
5	100% OPC	0.4	25	0.58	0.67	1.00	1.25	1.36
6	100% OPC	0.4	32	0.53	0.60	1.00	1.28	1.36
7	100% OPC	0.4	38	0.62	0.71	1.00	1.29	1.38
8	100% OPC	0.4	45	0.73	0.86	1.00	1.23	1.35
9	100% OPC	0.45	25	0.49	0.64	1.00	1.30	1.40
10	100% OPC	0.45	32	0.45	0.57	1.00	1.30	1.38
11	100% OPC	0.45	38	0.55	0.67	1.00	1.32	1.42
12	100% OPC	0.45	45	0.67	0.81	1.00	1.27	1.40
Average				**0.59**	**0.70**	**1.00**	**1.26**	**1.36**
13	OPC + 10% VFFA	0.4	25	0.46	0.56	1.00	1.26	1.37
14	OPC + 10% VFFA	0.4	32	0.55	0.62	1.00	1.28	1.43
15	OPC + 10% VFFA	0.4	38	0.56	0.61	1.00	1.31	1.45
16	OPC + 10% VFFA	0.4	45	0.61	0.69	1.00	1.27	1.38
Average				**0.54**	**0.62**	**1.00**	**1.28**	**1.41**
17	OPC + 30% FA	0.4	25	0.48	0.59	1.00	1.35	1.48
18	OPC + 30% FA	0.4	32	0.44	0.54	1.00	1.38	1.53
19	OPC + 30% FA	0.4	38	0.46	0.56	1.00	1.34	1.50
20	OPC + 30% FA	0.4	45	0.65	0.75	1.00	1.35	1.51
Average				**0.51**	**0.61**	**1.00**	**1.35**	**1.51**
21	OPC + 7% SF	0.4	25	0.59	0.67	1.00	1.26	1.40
22	OPC + 7% SF	0.4	32	0.54	0.61	1.00	1.27	1.40
23	OPC + 7% SF	0.4	38	0.60	0.70	1.00	1.26	1.39
24	OPC + 7% SF	0.4	45	0.73	0.85	1.00	1.24	1.40
Average				**0.62**	**0.71**	**1.00**	**1.26**	**1.40**
25	OPC + 70% GGBFS	0.4	25	0.48	0.60	1.00	1.45	1.60
26	OPC + 70% GGBFS	0.4	32	0.50	0.59	1.00	1.48	1.65
27	OPC + 70% GGBFS	0.4	38	0.47	0.57	1.00	1.46	1.57
28	OPC + 70% GGBFS	0.4	45	0.70	0.84	1.00	1.47	1.64
Average				**0.54**	**0.65**	**1.00**	**1.46**	**1.62**
29	OPC + 20% NP	0.4	25	0.51	0.62	1.00	1.36	1.48
30	OPC + 20% NP	0.4	32	0.53	0.60	1.00	1.34	1.48
31	OPC + 20% NP	0.4	38	0.52	0.59	1.00	1.37	1.50
32	OPC + 20% NP	0.4	45	0.61	0.71	1.00	1.38	1.55
Average				**0.54**	**0.63**	**1.00**	**1.36**	**1.50**

Table 4.5: Compressive Strength of Blended Cement Concretes Compared to the Strength of OPC Concrete (0.4 w/c) - Average of all Curing Regimes.

Mix No.	Cementitious Materials	w/c Ratio	Casting Temp. (°C)	f_c (Blended Cement) / f_c (OPC) [1]				
				3 Days	7 Days	28 Days	90 Days	180 Days
13	OPC + 10% VFFA	0.4	25	0.85	0.90	1.07	1.07	1.08
14	OPC + 10% VFFA	0.4	32	1.05	1.04	1.02	1.02	1.07
15	OPC + 10% VFFA	0.4	38	1.01	0.98	1.13	1.14	1.18
16	OPC + 10% VFFA	0.4	45	1.00	0.96	1.18	1.22	1.21
Average				**0.98**	**0.97**	**1.10**	**1.11**	**1.14**
17	OPC + 30% FA	0.4	25	0.80	0.85	0.96	1.03	1.05
18	OPC + 30% FA	0.4	32	0.79	0.87	0.97	1.04	1.09
19	OPC + 30% FA	0.4	38	0.82	0.88	1.10	1.15	1.20
20	OPC + 30% FA	0.4	45	0.86	0.85	0.97	1.06	1.08
Average				**0.82**	**0.86**	**1.00**	**1.07**	**1.11**
21	OPC + 7% SF	0.4	25	1.15	1.12	1.12	1.12	1.16
22	OPC + 7% SF	0.4	32	1.12	1.11	1.09	1.08	1.13
23	OPC + 7% SF	0.4	38	1.10	1.13	1.14	1.11	1.15
24	OPC + 7% SF	0.4	45	1.12	1.11	1.12	1.12	1.16
Average				**1.12**	**1.12**	**1.12**	**1.11**	**1.15**
25	OPC + 70% GGBFS	0.4	25	0.66	0.70	0.78	0.90	0.92
26	OPC + 70% GGBFS	0.4	32	0.68	0.72	0.73	0.84	0.89
27	OPC + 70% GGBFS	0.4	38	0.69	0.73	0.90	1.02	1.03
28	OPC + 70% GGBFS	0.4	45	0.73	0.74	0.75	0.90	0.92
Average				**0.69**	**0.72**	**0.79**	**0.92**	**0.94**
29	OPC + 20% NP	0.4	25	0.79	0.83	0.90	0.97	0.98
30	OPC + 20% NP	0.4	32	0.84	0.85	0.85	0.89	0.93
31	OPC + 20% NP	0.4	38	0.82	0.82	0.98	1.04	1.07
32	OPC + 20% NP	0.4	45	0.82	0.81	0.98	1.09	1.13
Average				**0.82**	**0.83**	**0.93**	**1.00**	**1.02**

[1] Ratio of compressive strength of blended cement concretes to plain cement concretes.

4.1.1 OPC Concrete

The compressive strength development of OPC concrete (100% OPC) specimens prepared with w/c ratio of 0.3, 0.4 or 0.45, cast at 25, 32, 38 or 45°C and cured under moist condition, covering with wet burlap or applying a curing compound is depicted in Figures 4.1 through 4.12.

Effect of Curing Period on Compressive Strength of OPC Concrete

The compressive strength increased with the period of curing in all the OPC concrete specimens. As expected, the increase in the compressive strength was very rapid in the early ages. Thereafter, the increase in the compressive strength was not that significant. The data presented in Table 4.4 summarizes the ratio of compressive strength development of OPC and blended cement concretes from 3 days to 180 days with respect to its 28-day strength. For all curing regimes, casting temperatures and w/c ratios utilized, it is noted that the average ratio of compressive strength of OPC concretes at 3-day to its 28-day was 0.59, which was higher than all the other cementitious materials except SF cement concretes, while the ratio of 180-day to 28-day was 1.36, which was lowest as compared to other cementitious materials.

Effect of Curing Regime on Compressive Strength of OPC Concrete

The compressive strength of the moist cured concrete specimens was noted to be more than that of the concrete specimens cured by covering with wet burlap or applying a curing compound. As shown in Tables 4.1 to 4.3, regardless of casting temperatures and w/c ratios investigated, the 28-day compressive strength of the moist cured concrete specimens was on average 10.1 and 16.9% more than that of the concrete specimens cured by covering with wet burlap or applying a curing compound, respectively.

Similarly, the compressive strength of the concrete specimens cured by covering with wet burlap was more than that of the concrete specimens cured by applying a curing compound by about 6.2% on average. The increase in strength development due to varying the curing technique is attributed to the water retention that preserves internal moisture for maintaining a favorable humid condition for hydration reaction. Unlike moist cured specimens which were cured and exposed in laboratory conditions, the lower strength in all the specimens cured under wet burlap or by the application of a curing compound, at all test ages, may be the consequence of its exposure to ambient weather conditions that accelerated the evaporation process. Hasnain et al. [69] observed that 50% rate of evaporation decreases when concrete specimens (cast at 32°C) were shaded as compared to those concrete samples which were kept in open air, during day time under hot weather conditions. Shalon [100] reported that concrete exhibited about 30 to 40% reduction in strength when cast and cured under hot weather but inadequately cured later on. Shoukry et al. [90] also observed degradation of compressive strength, split tensile strength and modulus of elasticity of concrete exposed at higher temperature (varied from -20 to 50°C). The minimum strength gain measured in compound-cured specimens is possibly due to its poor performance as compared to other curing compounds. Wang et al. [75] investigated the efficiency of five different curing membranes and found that the performance of water-based curing compound was the least.

Effect of Casting Temperature on Compressive Strength of OPC Concrete

For all w/c ratios and curing regimes, the compressive strength increased with the increase in casting temperature during early ages of up to 7 days, as shown in Tables 4.1

to 4.3. On average, the 3- and 7-day compressive strength of concrete specimens cast at 45°C was 22.5, 16.0 and 6.8% higher than that of the specimens cast at 25, 32 and 38°C, respectively. However, at later ages of 28 to 180 days, the maximum compressive strength was noted in the mixes that were cast at 32°C followed by those that were cast at 38°C, while the compressive strength of the concrete specimens cast at 25 or 45°C was almost similar but lower than those cast at other temperatures, as depicted in Figures 4.13 through 4.18. On average, the 28-day compressive strength of the concrete specimens cast at 32°C was 16.6, 6.5 and 19.5% more than that of the concrete specimens cast at 25, 38 or 45°C, respectively. Al-Gahtani et al. [1] found that 35°C was the optimum casting temperature for the 28-day compressive strength development in OPC concrete specimens out of a range of concrete placement temperatures of 26, 35, 38, 41 and 44°C. They concluded that lower strength at lower concrete temperature is due to its sudden exposure to hot weather that results in non-uniform distribution of the hydration products and/or microcracking. Conversely, Abbasi and Tayyib [83] observed that with the increase in concrete mix temperature at the time of placement (ranging from 24 to 47°C), cured in water or wet burlap, both the pulse velocity and modulus of elasticity of concrete are lessened under hot weather condition. They found that concrete cast at 45°C and cured in hot environment can lead to a reduction in modulus of elasticity of about 17.5%. However, in another early study [82], Abbasi and Tayyib reported that the optimum concrete temperature at which maximum compressive strength (using Type I cement) achieved was 32 to 34°C out of a range of temperature investigated between 24 to 46°C and moist cured in oven under simulated hot weather condition or in atmospheric temperature. It was also found that the splitting tensile strength and modulus of rupture of concrete could be reduced by 11 and 22%, respectively, at increased casting temperature. Moreover, Abbasi et al. [81] observed that the strength of the reinforced concrete beams cast and cured under hot weather could be decreased by about 25% when the concrete mixture temperature approaches to about 45°C.

Since most of the studies carried out in past were related to curing temperature of concrete, which is well documented. The results of this study, which is related to casting temperature, has also shown somehow the same behavior on mechanical properties.

Despite the fact that a high temperature at the time of concrete placement and setting tends to enhance the early strength gain, there is an adverse effect on the later (7 days onwards) strength gain. This is attributed to the accelerated early hydration that forms porous structure leading to degradation of strength at later periods compared to the slow cement hydration that increases the gel/space ratio in the interstices [32]. The increase in the rate of hydration at higher temperature is true for any type of cement [32]. The positive effect of elevated curing temperature on the early strength of blended cement mortar may be due to the combined reaction of heat of hydration and pozzolana [11]. However, the harmful effects of high initial temperature on later strength is addressed by many authors [101,102]. They concluded that the early concrete strength increases with the rise in the early curing temperature due to the rapid rate of hydration. Conversely, due to non-uniform diffusion of hydration products and the difference in the coefficient of thermal expansion of concrete constituents, the cement paste becomes porous and even microcracks may form, which adversely affect the long-term strength. Kefeng and Nichols [89] suggested that the adverse effect of elevated curing temperature on later strength reduction can be alleviated by incorporating SF and FA cement into concrete.

Further the effect of curing temperature in the range of about 12 to 50°C on the compressive strength at 1- and 28-day was evaluated by testing concrete specimens after cooling to 23°C for 2 hours [103]. It was noted that with the increase in temperature, the compressive strength increased from 3 to 16 MPa after 1 day, whereas strength decreased from 41 to 30 MPa after 28 days. Price [85] also observed that a higher temperature resulted in higher early strength but beyond the age of 1 to 4 weeks, a reversal in strength occurred. He further noted that there was greater retrogression when concrete was cured at high temperatures of 32 to 49°C, while there appeared an optimum temperature that resulted in the maximum strength when cured at low temperatures of 4 to 23°C. Kim et al. [104] carried out an experimental investigation on the effect curing temperature ranging from 10 to 50°C on the compressive and split tensile strength using Type I, V and V cement + fly ash concretes and tested after 1, 3, 7, and 28 days. They reported that early compressive and split tensile strength increased with a rise in temperatures but the later strengths became lower as compared to normal temperatures. Klieger [86] observed about 15% reduction in the concrete strength of OPC at 41°C as compared to that produced at 23°C after 7 days of curing in the range of -4 to 49°C, unlike increase in strength up to 7 days.

Effect of w/c Ratio on Compressive Strength of OPC Concrete

The compressive strength of the OPC concrete mixes decreased with the increase in w/c ratio, as expected. Irrespective of casting temperature and curing regime, the 28-day compressive strength of the mixes prepared with a w/c ratio of 0.3 was on average 18.5 and 31.3% more than that of the mixes prepared with the w/c ratio of 0.4 or 0.45, respectively, as shown in Tables 4.1 to 4.3. Further, the compressive strength of the concrete specimens prepared with w/c ratio of 0.4 was on average 10.8% more than that of the concrete specimens prepared with w/c ratio of 0.45. The decrease in the compressive strength with an increase in the w/c ratio may be due to the space occupied by the excessive water in concrete matrix thereby making it less dense. Ait-Aider et al. [68] showed that unlike normal conditions, concreting under hot environmental conditions with the limited addition of extra amount of water, i.e. the increase in the w/c ratio, has no adverse effect on strength of concrete and also advantageous in compensating the mixing water lost by evaporation and in maintaining the desired workability. On contrary, several researches mentioned the harmful effect of increased w/c ratio on the properties of concrete. Neville [32] addressed that the rate of strength gain of concrete is influenced by the w/c ratio in that the mixes with low w/c attains strength rapidly than mixes having high w/c ratio because in concrete with low w/c ratio, the cement particles are nearer to each other and forming a system of continuity of gel very quickly. Al-Amoudi et al. [11] reported that the long-term compressive strength of OPC, FA, BFS cement mortar specimens prepared with a w/cm ratio of 0.3 is higher than that of the specimens prepared at 0.4 w/cm ratio under elevated temperature exposure. Kefeng and Nichols [89] also mentioned that the effect of later strength reduction can be minimized by reducing the w/c ratio because at low w/c ratio, cement particles are well packed and lesser hydration products is sufficient to fill the gaps between them. A study [105] showed that higher temperature and the lower w/c ratio tends to speed up the setting time of concrete and a reduction of about 50% in the initial setting time was observed when either concrete temperature was changed from 28 to 46°C or w/c ratio was varied from 0.4 to 0.6. However, high temperature leads to lower long-term strength.

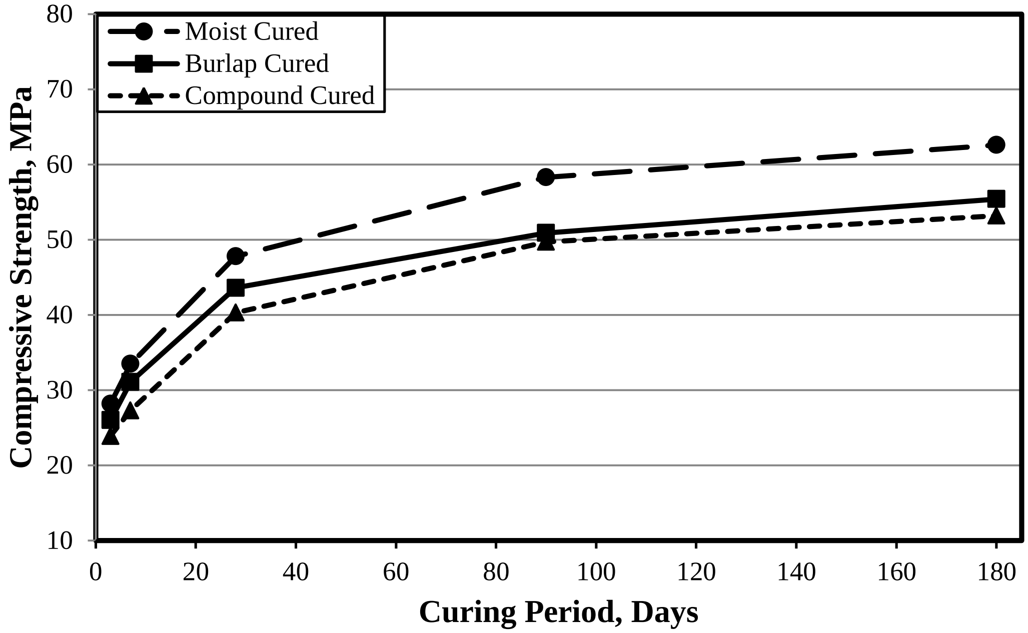

Figure 4.1: Compressive Strength Development of OPC Concrete Prepared with w/c Ratio of 0.3 and Cast at 25°C.

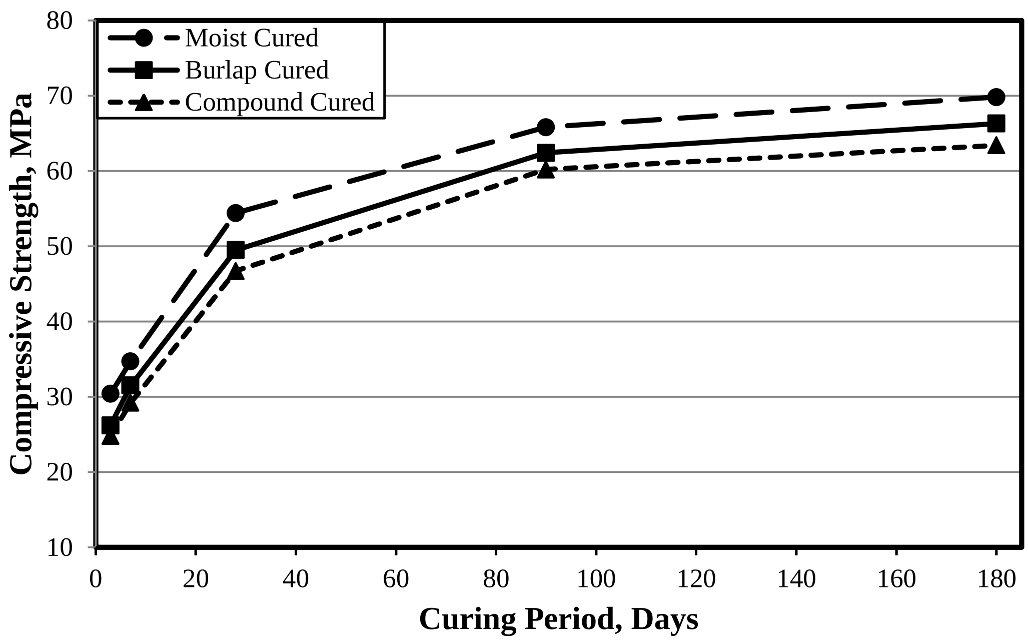

Figure 4.2: Compressive Strength Development of OPC Concrete Prepared with w/c Ratio of 0.3 and Cast at 32°C.

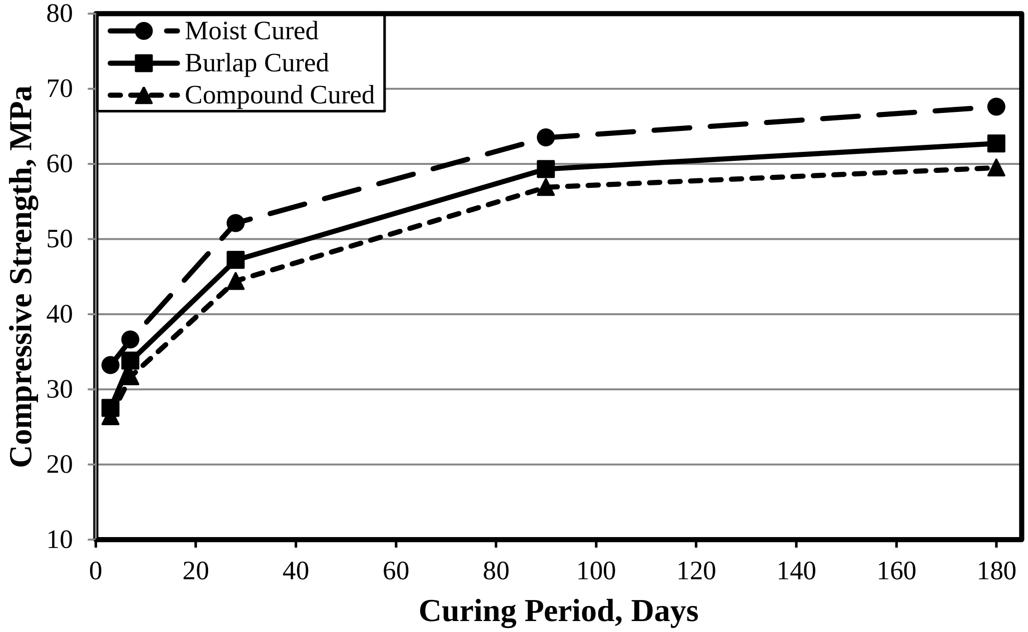

Figure 4.3: Compressive Strength Development of OPC Concrete Prepared with w/c Ratio of 0.3 and Cast at 38°C.

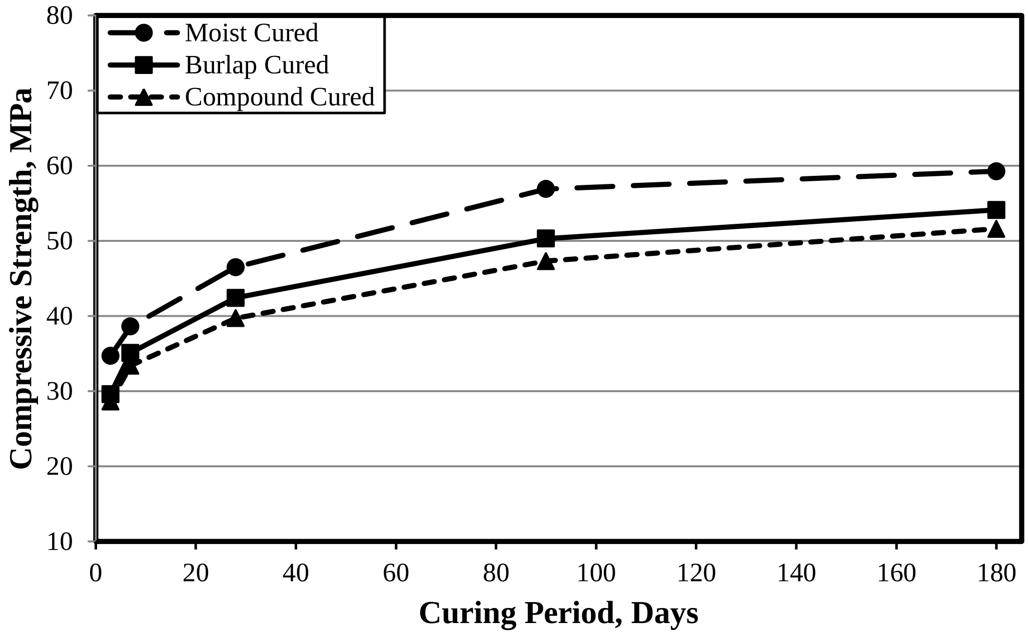

Figure 4.4: Compressive Strength Development of OPC Concrete Prepared with w/c Ratio of 0.3 and Cast at 45°C.

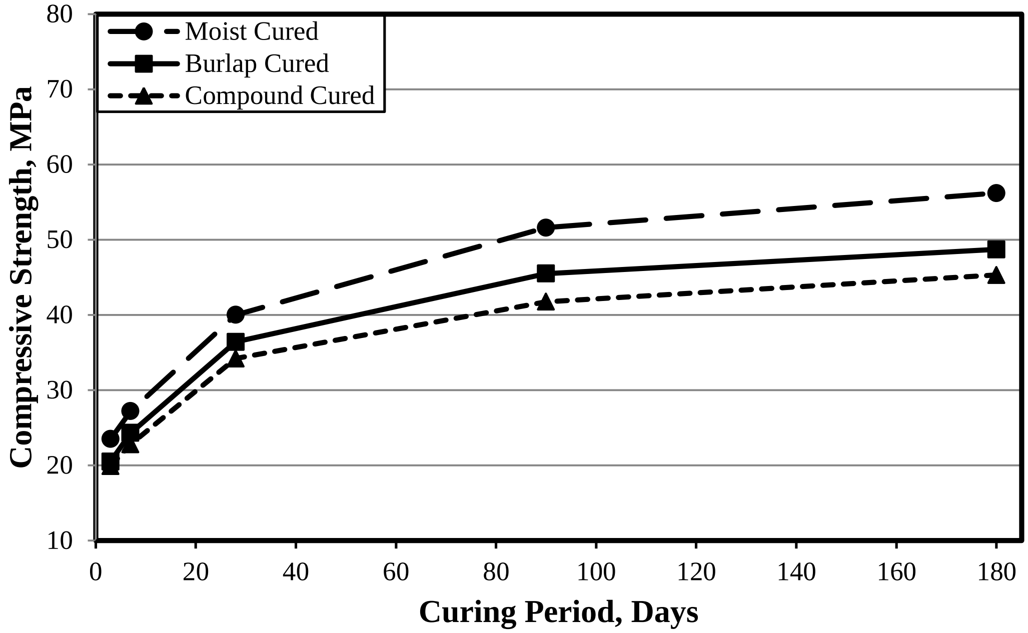

Figure 4.5: Compressive Strength Development of OPC Concrete Prepared with w/c Ratio of 0.4 and Cast at 25°C.

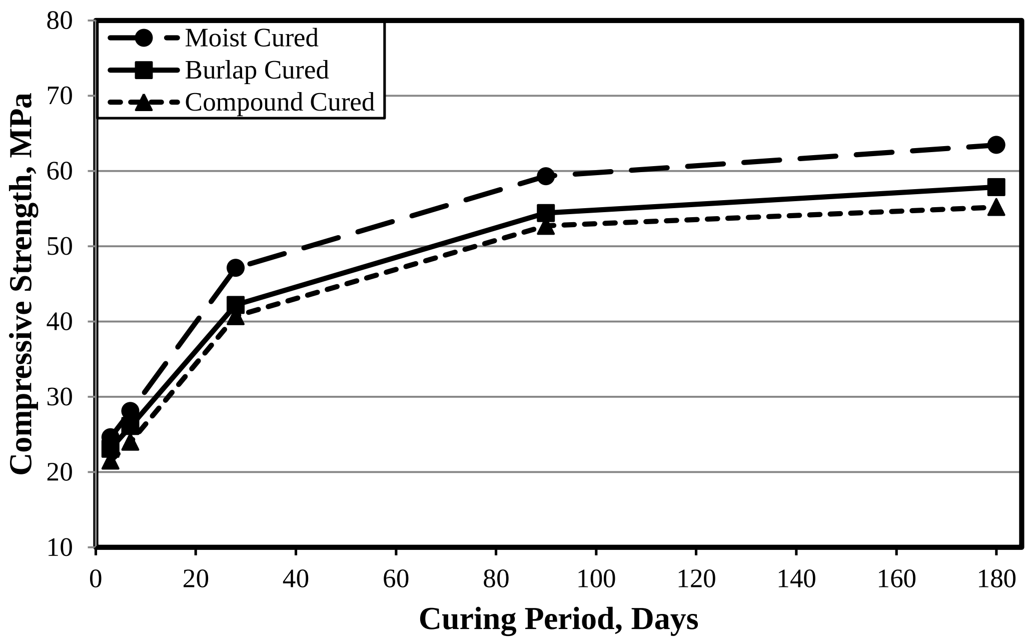

Figure 4.6: Compressive Strength Development of OPC Concrete Prepared with w/c Ratio of 0.4 and Cast at 32°C.

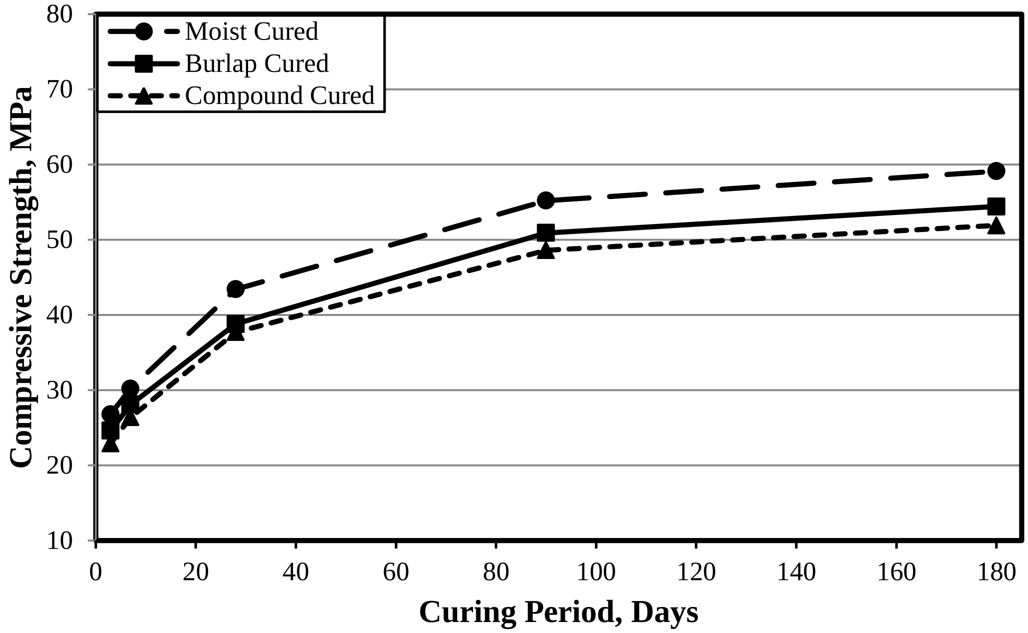

Figure 4.7: Compressive Strength Development of OPC Concrete Prepared with w/c Ratio of 0.4 and Cast at 38°C.

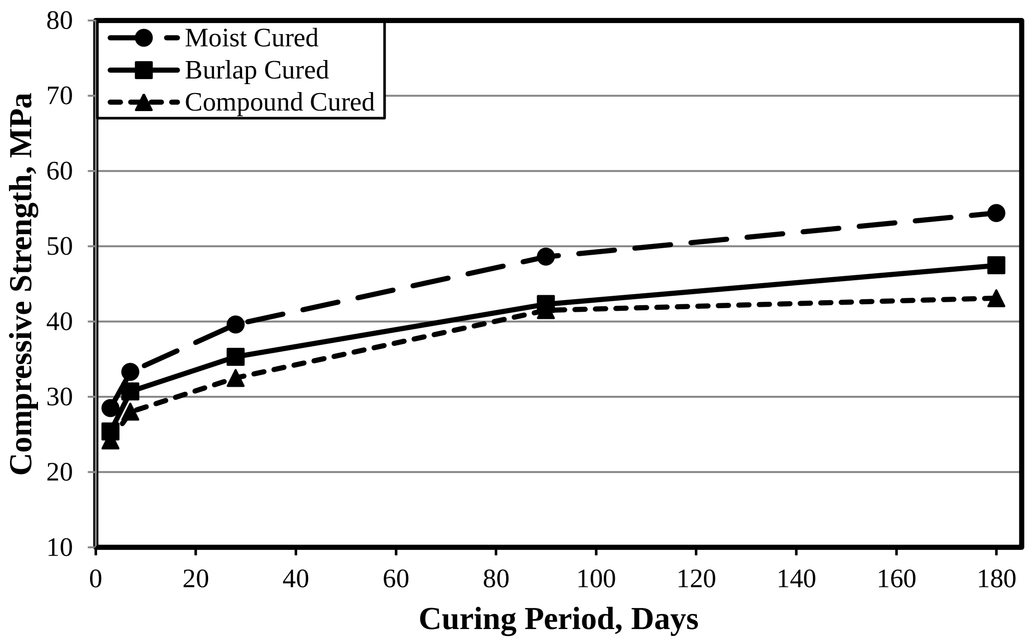

Figure 4.8: Compressive Strength Development of OPC Concrete Prepared with w/c Ratio of 0.4 and Cast at 45°C.

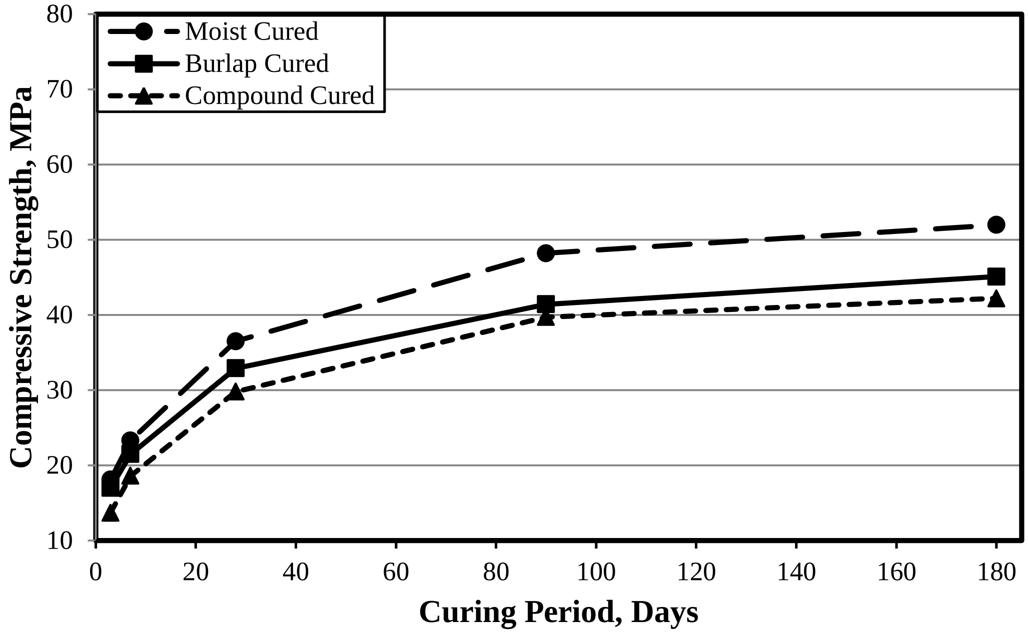

Figure 4.9: Compressive Strength Development of OPC Concrete Prepared with w/c Ratio of 0.45 and Cast at 25°C.

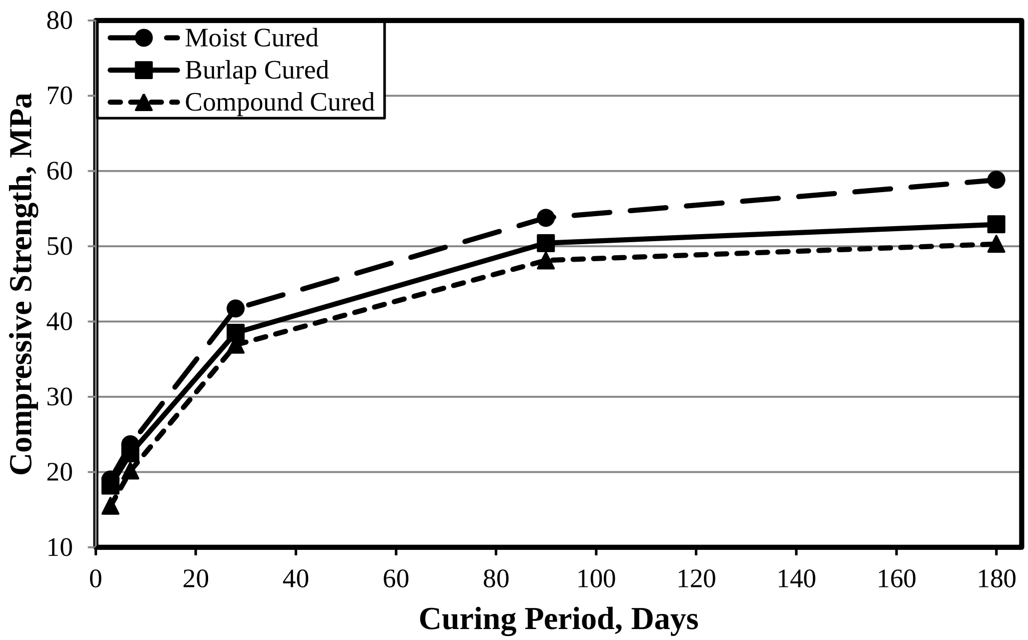

Figure 4.10: Compressive Strength Development of OPC Concrete Prepared with w/c Ratio of 0.45 and Cast at 32°C.

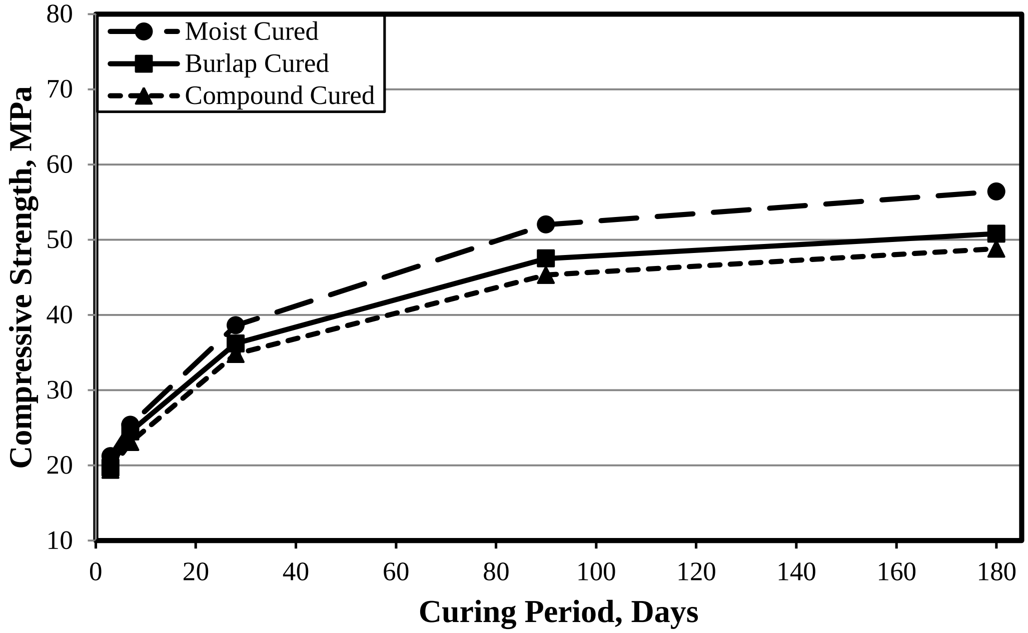

Figure 4.11: Compressive Strength Development of OPC Concrete Prepared with w/c Ratio of 0.45 and Cast at 38°C.

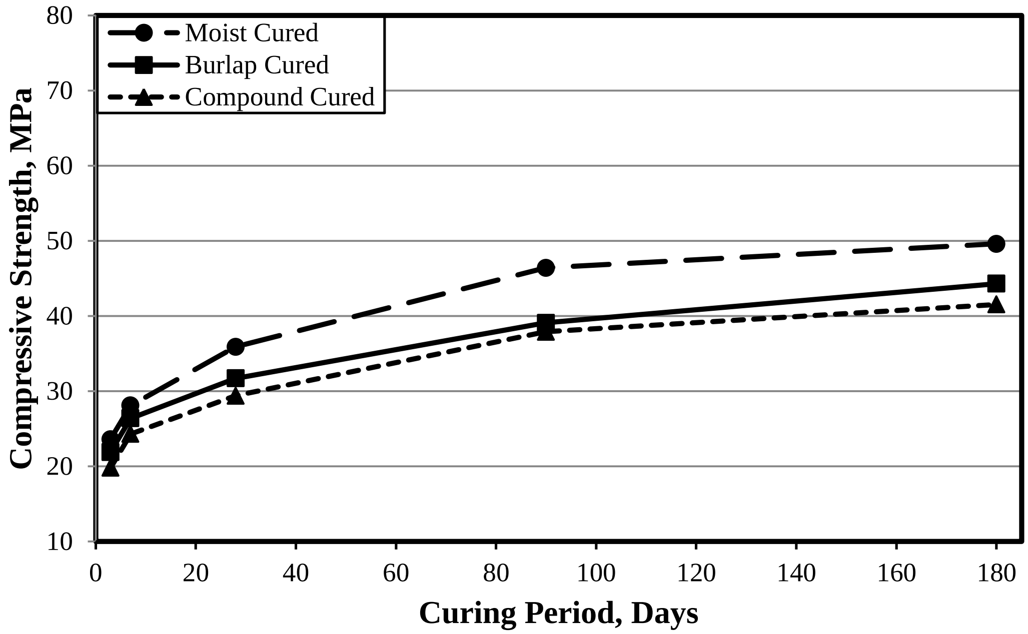

Figure 4.12: Compressive Strength Development of OPC Concrete Prepared with w/c Ratio of 0.45 and Cast at 45°C.

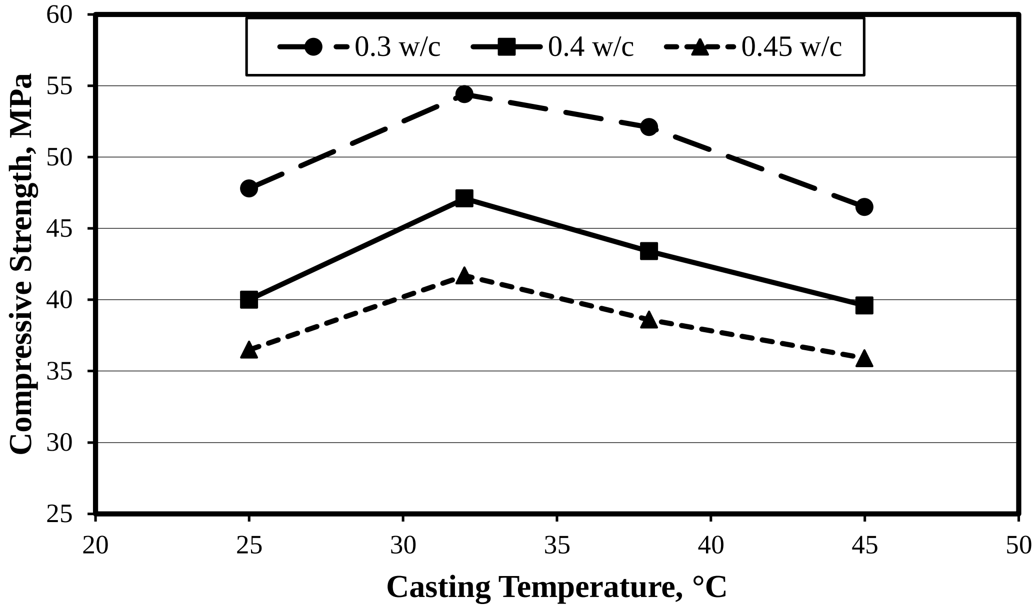

Figure 4.13: Compressive Strength of OPC Concretes Prepared with w/c Ratio of 0.3-0.45 and Cast at 25-45°C after 28 Days of Moist Curing.

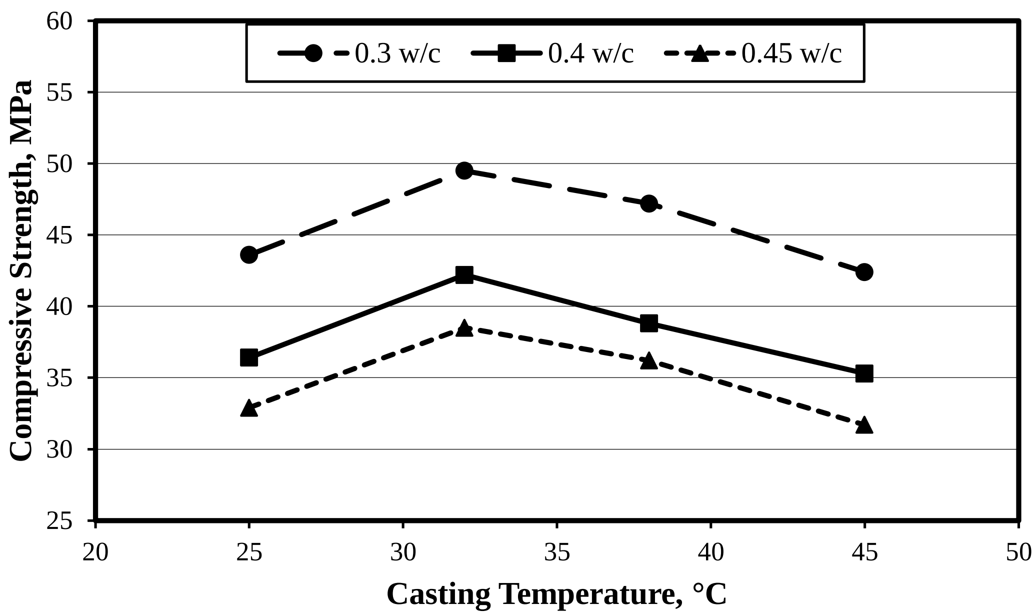

Figure 4.14: Compressive Strength of OPC Concretes Prepared with w/c Ratio of 0.3-0.45 and Cast at 25-45°C after 28 Days of Curing by Covering with Wet Burlap.

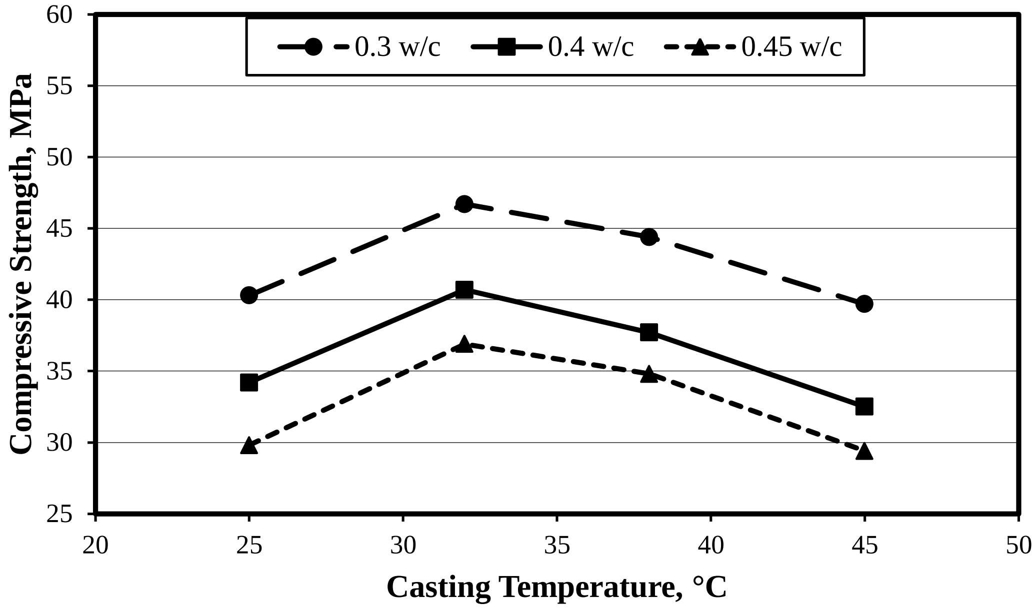

Figure 4.15: Compressive Strength of OPC Concretes Prepared with w/c Ratio of 0.3-0.45 and Cast at 25-45°C after 28 Days of Applying a Curing Compound.

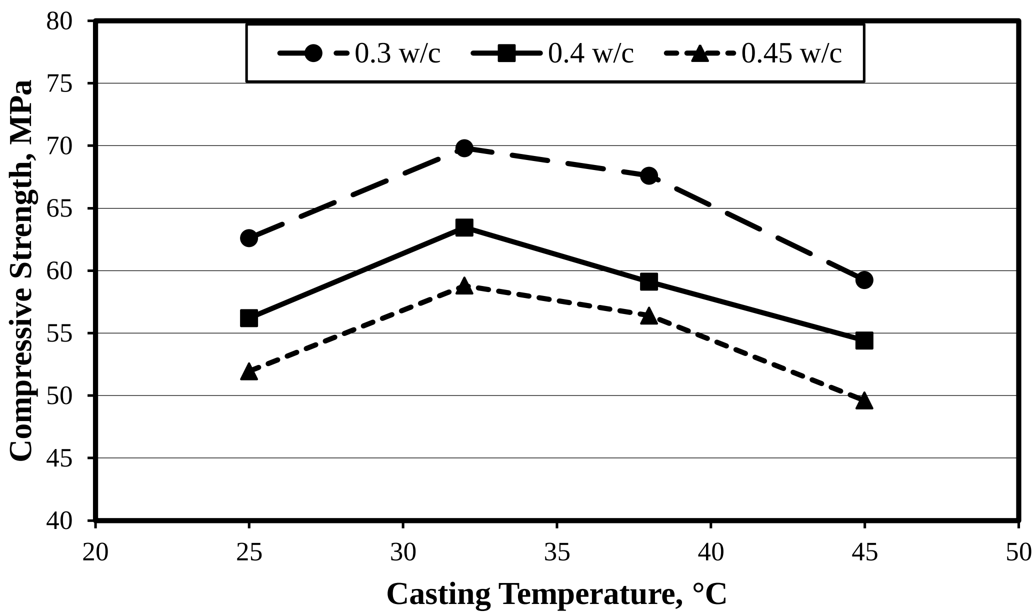

Figure 4.16: Compressive Strength of OPC Concretes Prepared with w/c Ratio of 0.3-0.45 and Cast at 25-45°C after 180 Days of Moist Curing.

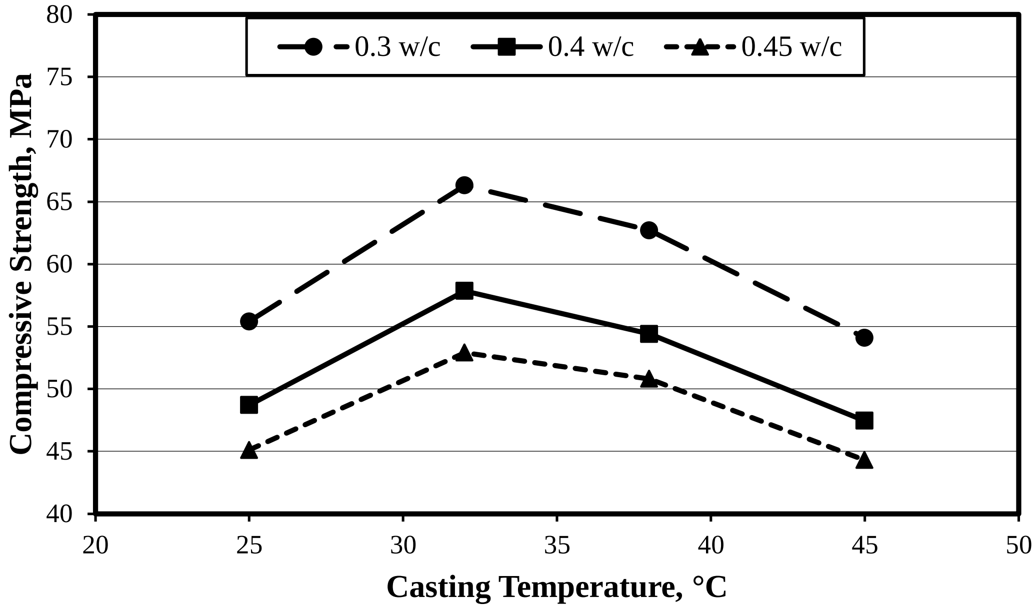

Figure 4.17: Compressive Strength of OPC Concretes Prepared with w/c Ratio of 0.3-0.45 and Cast at 25-45°C after 180 Days of Curing by Covering with Wet Burlap.

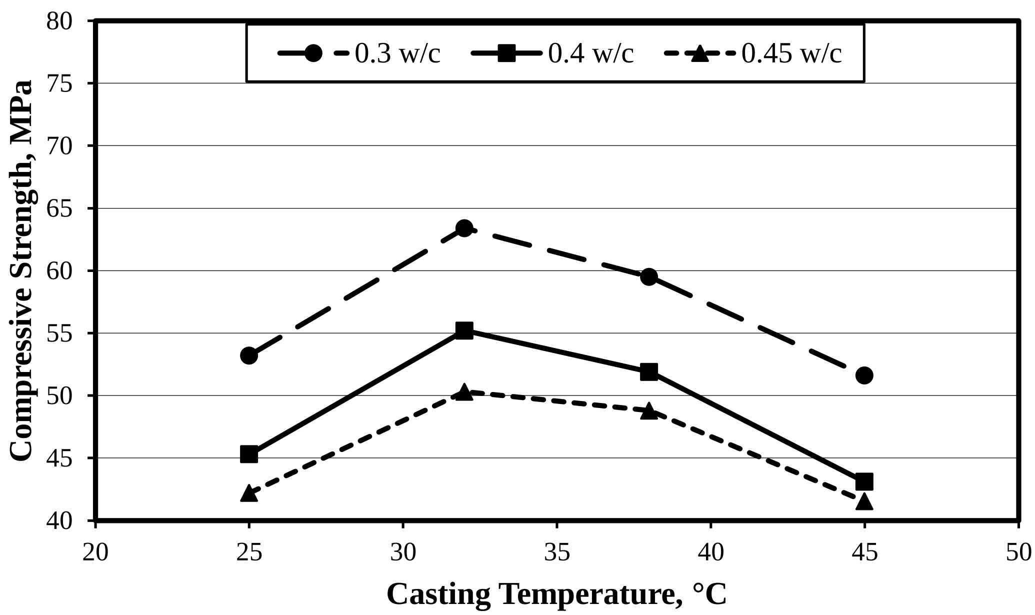

Figure 4.18: Compressive Strength of OPC Concretes Prepared with w/c Ratio of 0.3-0.45 and Cast at 25-45°C after 180 Days of Applying a Curing Compound.

4.1.2 VFFA Cement Concrete

The compressive strength development of VFFA cement concrete (OPC + 10% VFFA) specimens prepared with a w/cm ratio of 0.4, cast at 25, 32, 38 or 45°C and cured under moist condition, covering with wet burlap or applying a curing compound is depicted in Figures 4.19 through 4.22.

Effect of Curing Period on Compressive Strength of VFFA Cement Concrete

The compressive strength increased with age (i.e. curing and/or exposure period) in all the concrete specimens. As expected, the increase in the compressive strength was sharp in the early ages as well as at later ages due to the high reactivity and pozzolanic reaction of VFFA cement particles. Irrespective of any curing regime and casting temperature investigated, it is noted that the average ratio of compressive strength of VFFA cement concretes at 3-day to its 28-day was 0.54, which was marginally equal to the corresponding ratios of GGBFS and NP cement concretes. However, the ratio of 180- to 28-day was 1.41, which was comparable to SF cement concretes and indicates that the pozzolanic reaction is highly beneficial and requires longer period of curing to develop more compressive strength as compared to OPC.

Effect of Curing Regime on Compressive Strength of VFFA Cement Concrete

For all casting temperatures, the 28-day compressive strength of the moist cured specimens was on average 9.0 and 15.3% more than that of the concrete specimens cured by covering with wet burlap or applying a curing compound, respectively, as shown in Tables 4.1 to 4.3. Furthermore, the compressive strength of the concrete specimens cured by covering with wet burlap was more than that of the concrete specimens cured by applying a curing compound by about 5.8% on average. This difference in the rate of strength development due to varying the curing technique may be ascribed to the water retention that preserves internal moisture for maintaining a favorable humid condition for the hydration of cement and pozzolanic reactions.

Effect of Casting Temperature on Compressive Strength of VFFA Cement Concrete

Regardless of any curing regime used, the compressive strength increased with the increase in casting temperature during early ages of up to 7 days, as shown in Tables 4.1 to 4.3. On average, the 3- and 7-day compressive strength of concrete specimens cast at 45°C was 36.7, 7.6 and 5.1% more than that of the specimens cast at 25, 32 and 38°C, respectively. On the contrary, at later ages of 28 to 180 days, 38°C was the optimum temperature at which the maximum compressive strength was noted in the concrete specimens followed by those that were cast at 32 or 45°C, while the lowest compressive strength was observed in the concrete specimens cast at 25°C, as shown in Tables 4.1 through 4.3 and depicted in Figures 4.23-4.24. On average, the 28-day compressive strength of the concrete specimens cast at 38°C was 14.2, 2.3 and 6.4% greater than that of the concrete specimens cast at 25, 32 or 45°C, respectively.

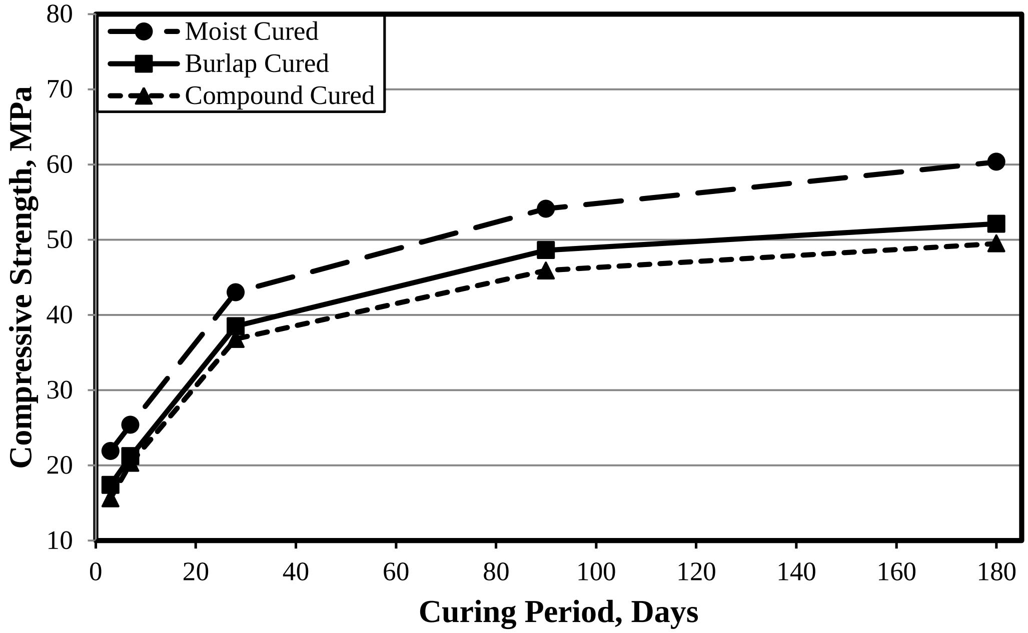

Figure 4.19: Compressive Strength Development of VFFA Cement Concrete Prepared with w/cm Ratio of 0.4 and Cast at 25°C.

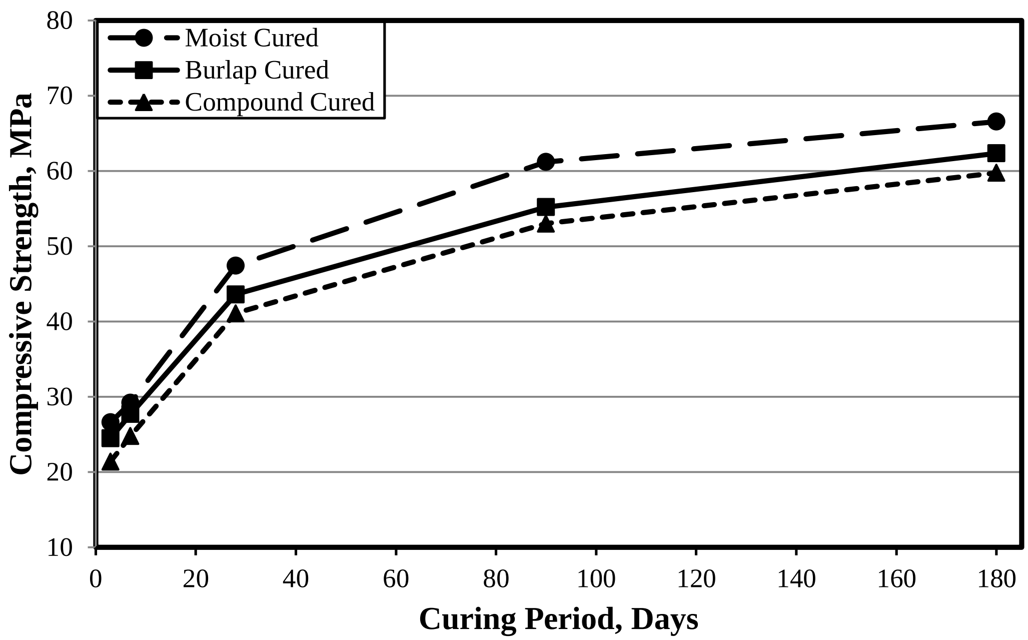

Figure 4.20: Compressive Strength Development of VFFA Cement Concrete Prepared with w/cm Ratio of 0.4 and Cast at 32°C.

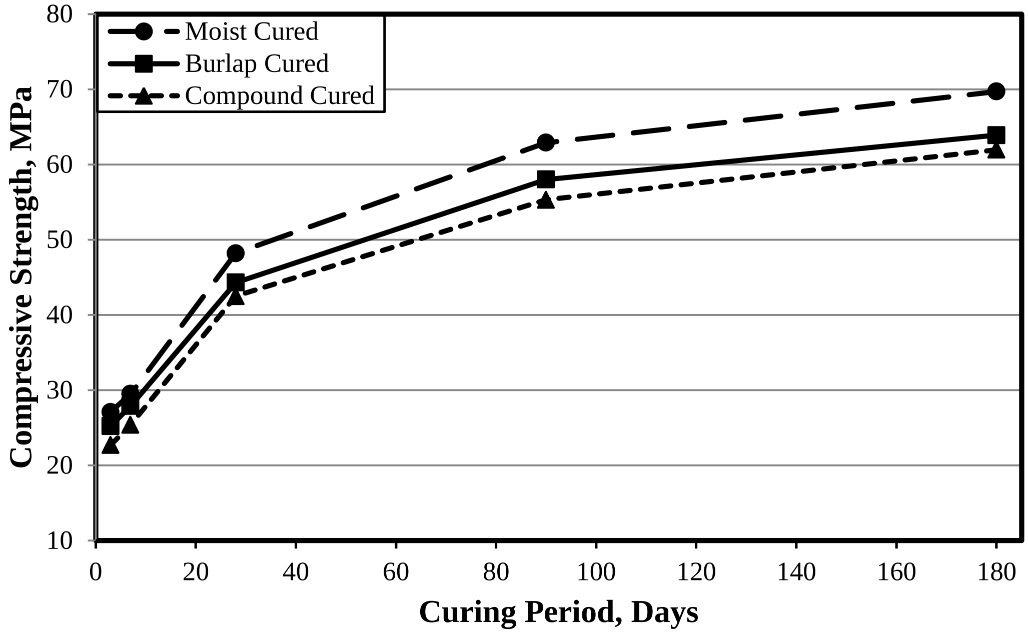

Figure 4.21: Compressive Strength Development of VFFA Cement Concrete Prepared with w/cm Ratio of 0.4 and Cast at 38°C.

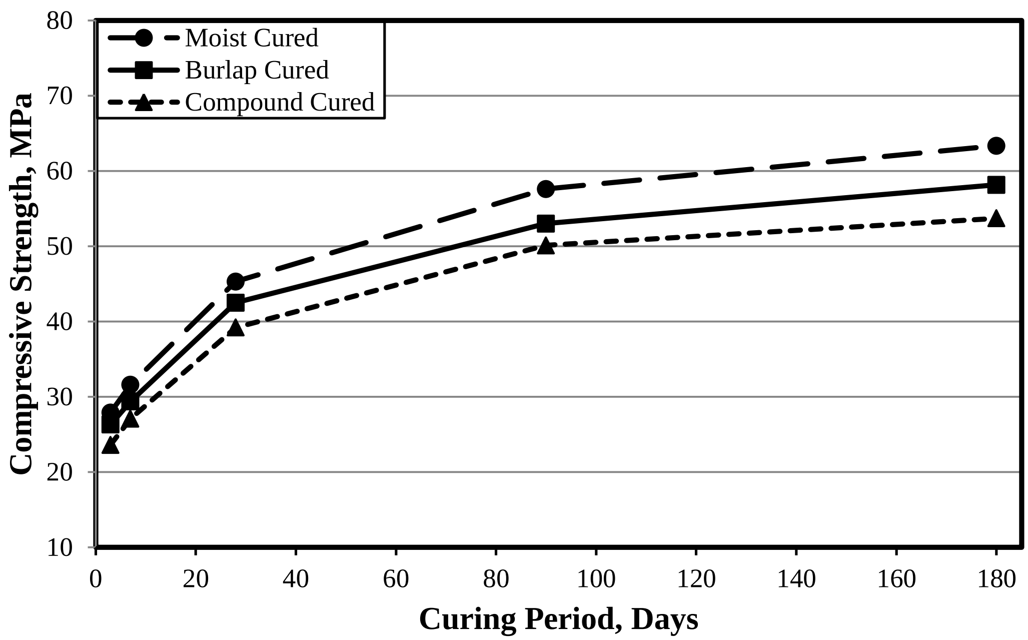

Figure 4.22: Compressive Strength Development of VFFA Cement Concrete Prepared with w/cm Ratio of 0.4 and Cast at 45°C.

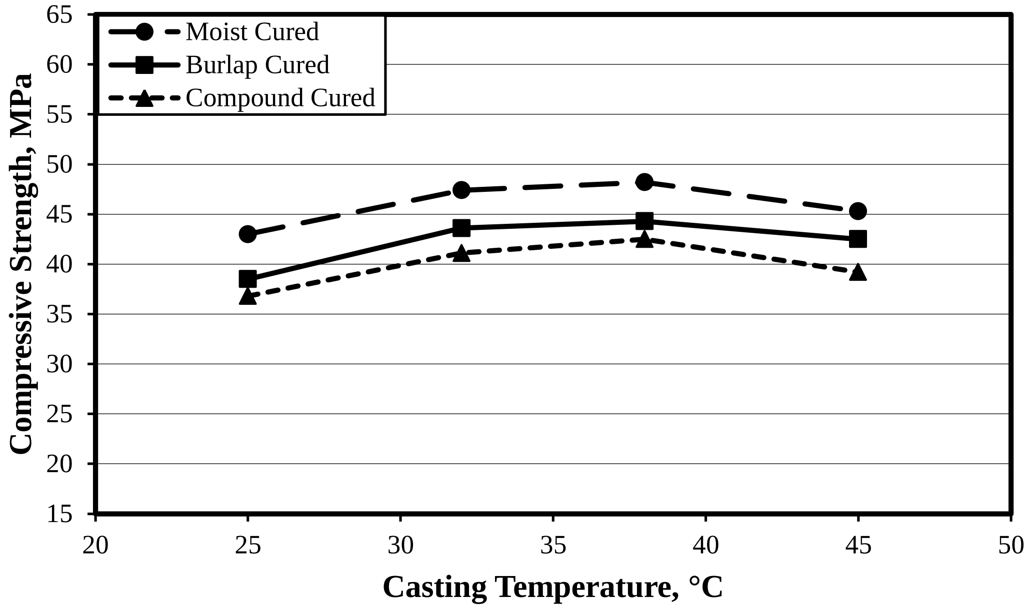

Figure 4.23: Compressive Strength of VFFA Cement Concretes at 28 Days.

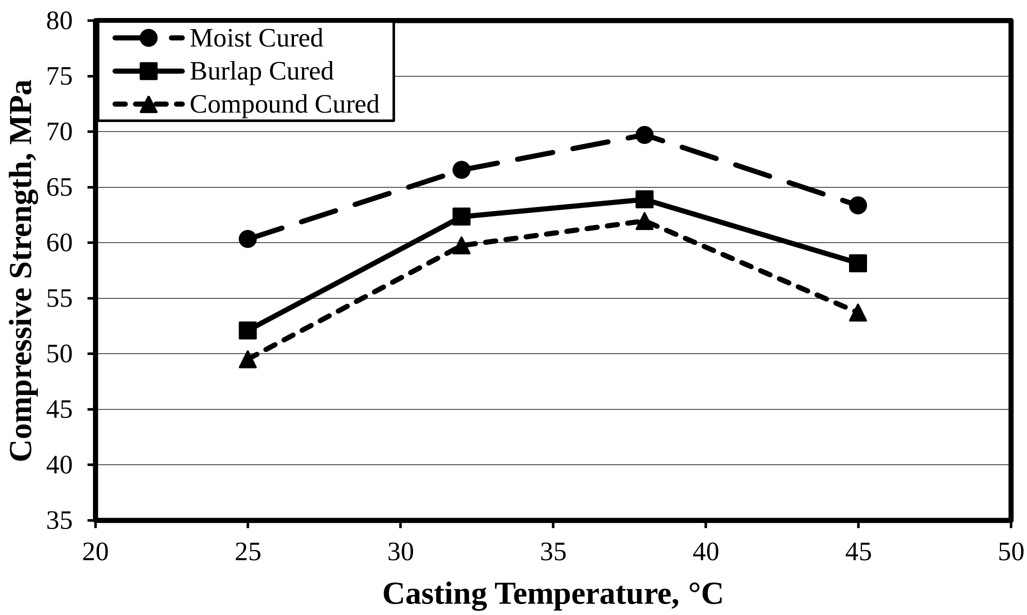

Figure 4.24: Compressive Strength of VFFA Cement Concretes at 180 Days.

4.1.3 FA Cement Concrete

The influence of partial replacement of OPC by 30% FA on the compressive strength is discussed in this section. For each curing regime, the compressive strength versus age (i.e. curing and/or exposure period) curves were plotted for all the concrete specimens prepared with a w/cm ratio of 0.4 and cast at 25, 32, 38 or 45°C, as shown in Figures 4.25 through 4.28.

Effect of Curing Period on Compressive Strength of FA Cement Concrete

The compressive strength increased with the age in all the concrete specimens. As expected, the early compressive strength developed slowly while at later ages the strength increased sharply due to the pozzolanic reaction. The average ratio of compressive strength of FA cement concrete at 3-day to its 28-day was 0.51, which was the lowest as compared to other cementitious materials whereas the ratio of 180-day to 28-day was 1.51, which was highest after GGBFS cement concretes. The results of several researches also revealed that incorporation of FA cement into plain cement decelerates the rate of hardening and early strength development of concrete, and since the heat of hydration is reduced, the FA cement concrete requires a long curing period to consume all the pozzolanic materials in the pozzolanic reaction [92,106]. Thomas et al. [107] also noted that initial strength gain of FA cement concrete was lower than that of OPC concrete. However, rate of strength development becomes higher in FA cement concretes after 28 days of curing.

Effect of Curing Regime on Compressive Strength of FA Cement Concrete

The highest compressive strength was noted in all the concrete specimens cured under moist condition followed by those specimens that were cured by covering with wet burlap or applying a curing compound, in decreasing order. On average, the 28-day compressive strength of the moist cured specimens was 8.5 and 10.8% more than that of the concrete specimens cured by covering with wet burlap or applying a curing compound, respectively, as shown in Tables 4.1 to 4.3. Further, the compressive strength of the concrete specimens cured by covering with wet burlap was 2.1% more than that of the concrete specimens cured by application of a curing compound. The effect of curing on strength of FA cement concrete is of paramount importance because the reactivity of FA cement is slow and hence prolonged wet-curing is necessary [32].

Effect of Casting Temperature on Compressive Strength of FA Cement Concrete

During the early ages of up to 7 days, the highest compressive strength was obtained in concrete specimens cast at 45°C, while the strength was reduced with the decrease in casting temperature, as shown in Tables 4.1 to 4.3. On average, the 3- and 7-day compressive strength of concrete specimens cast at 45°C was 27.6, 18.1 and 7.3% more than that of the specimens cast at 25, 32 and 38°C, respectively. Nonetheless, at the later ages of 28, 90 and 180 days, the maximum compressive strength was achieved in the concrete specimens cast at 38°C followed by those that were cast at 32°C, while the compressive strength of the concrete specimens cast at 25 and 45°C was almost similar and relatively low, as shown in Tables 4.1 through 4.3 and depicted in Figures 4.29-4.30. The 28-day compressive strength of the concrete specimens cast at 38°C was on average 24.9, 5.3 and 27.5% greater than that of the concrete specimens cast at 25, 32 or 45°C, respectively. The higher strength at the casting temperature of 38°C may be attributed to its slow and steady reactivity. However, the drop in strength at higher temperature is possibly due to the sensitivity of FA cement to temperature; especially under mass concreting when there is a rise in concrete temperature occurs which leads to the low strength hydration products [32].

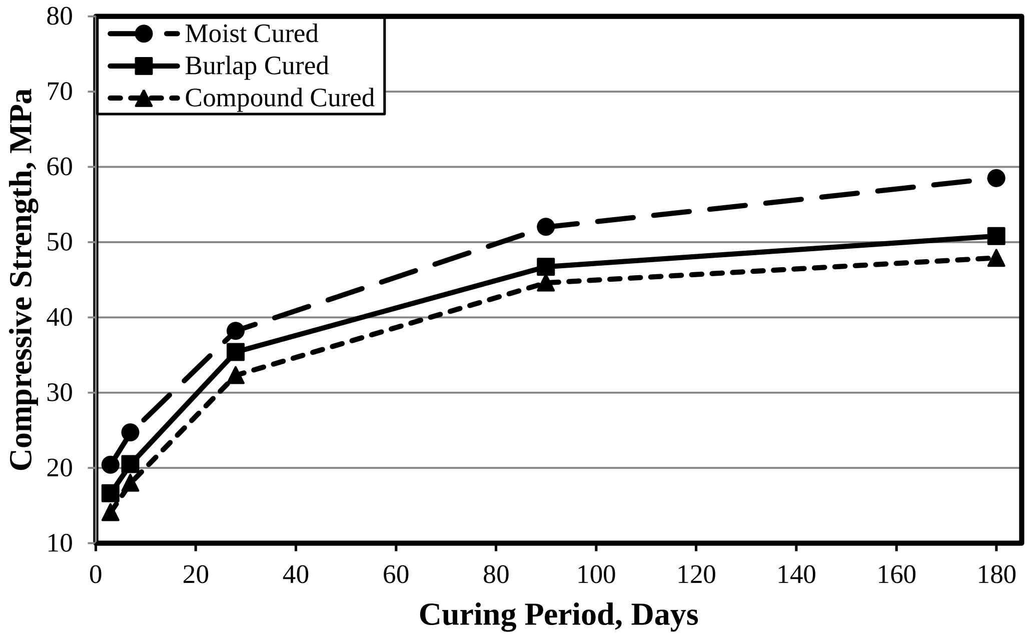

Figure 4.25: Compressive Strength Development of FA Cement Concrete Prepared with w/cm Ratio of 0.4 and Cast at 25°C.

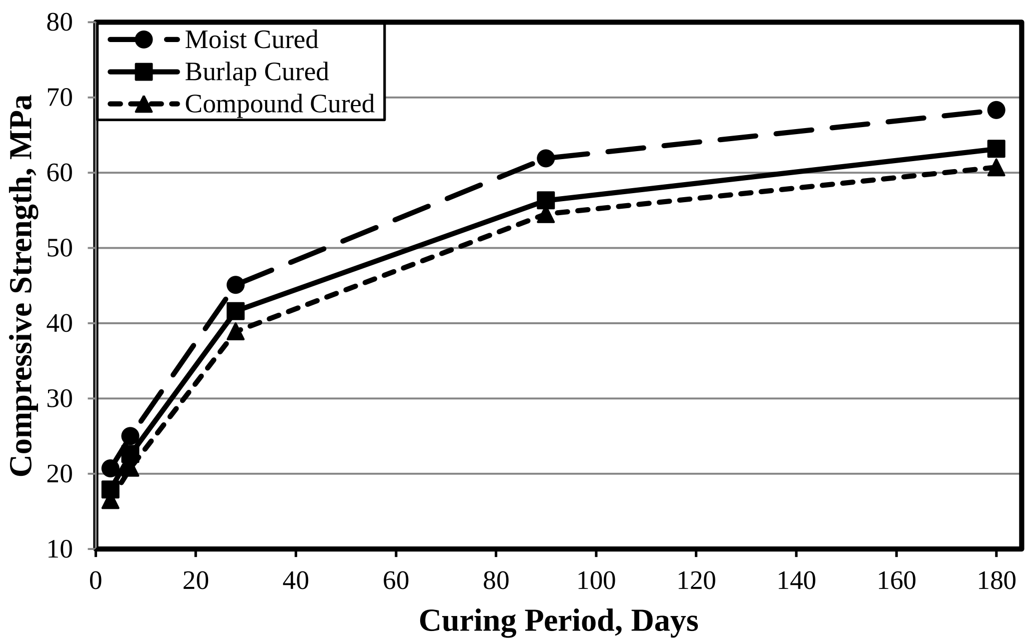

Figure 4.26: Compressive Strength Development of FA Cement Concrete Prepared with w/cm Ratio of 0.4 and Cast at 32°C.

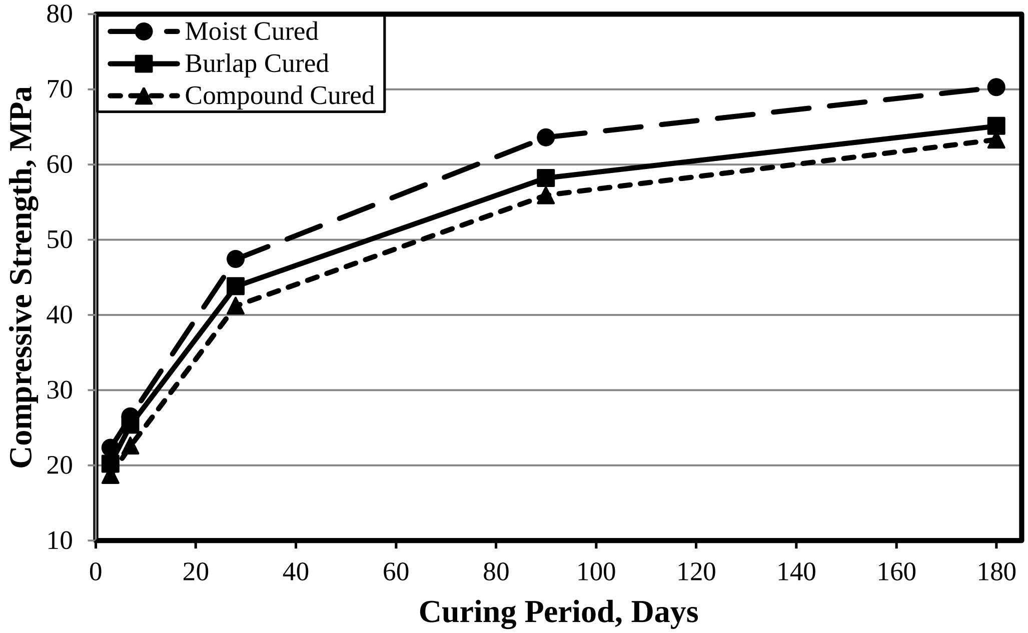

Figure 4.27: Compressive Strength Development of FA Cement Concrete Prepared with w/cm Ratio of 0.4 and Cast at 38°C.

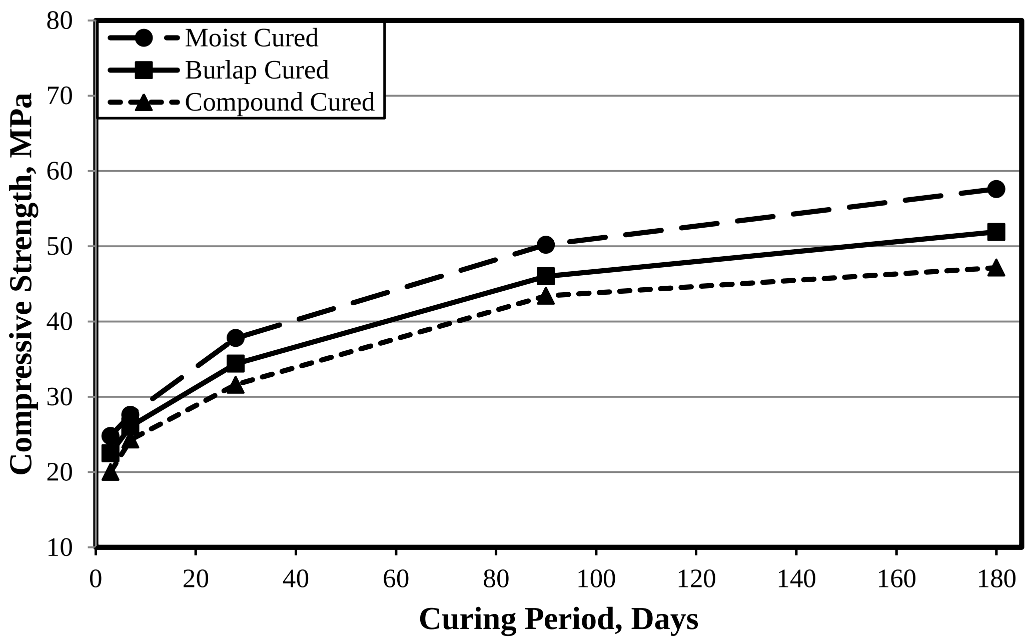

Figure 4.28: Compressive Strength Development of FA Cement Concrete Prepared with w/cm Ratio of 0.4 and Cast at 45°C.

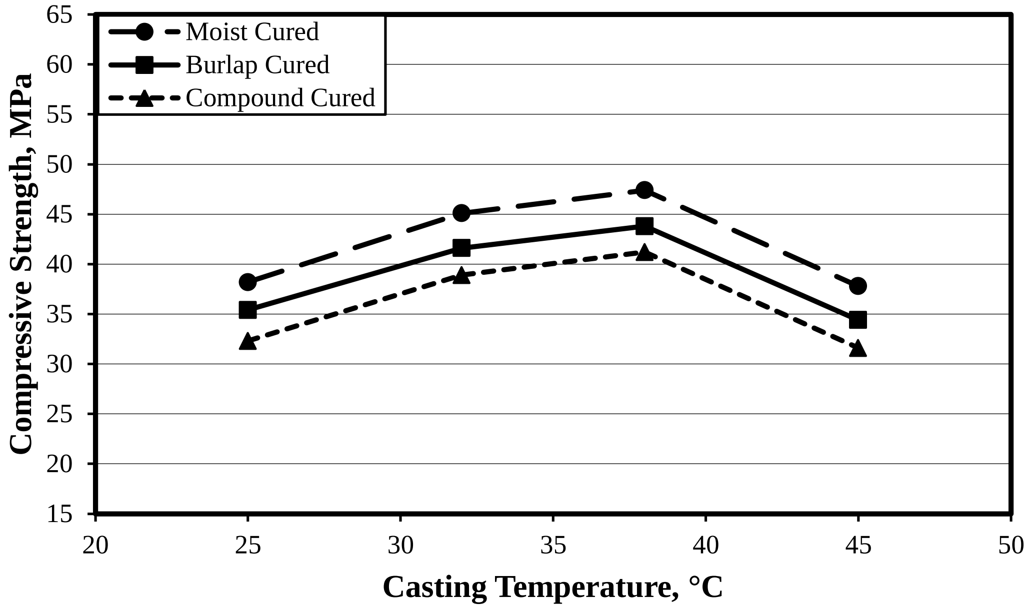

Figure 4.29: Compressive Strength of FA Cement Concretes at 28 Days.

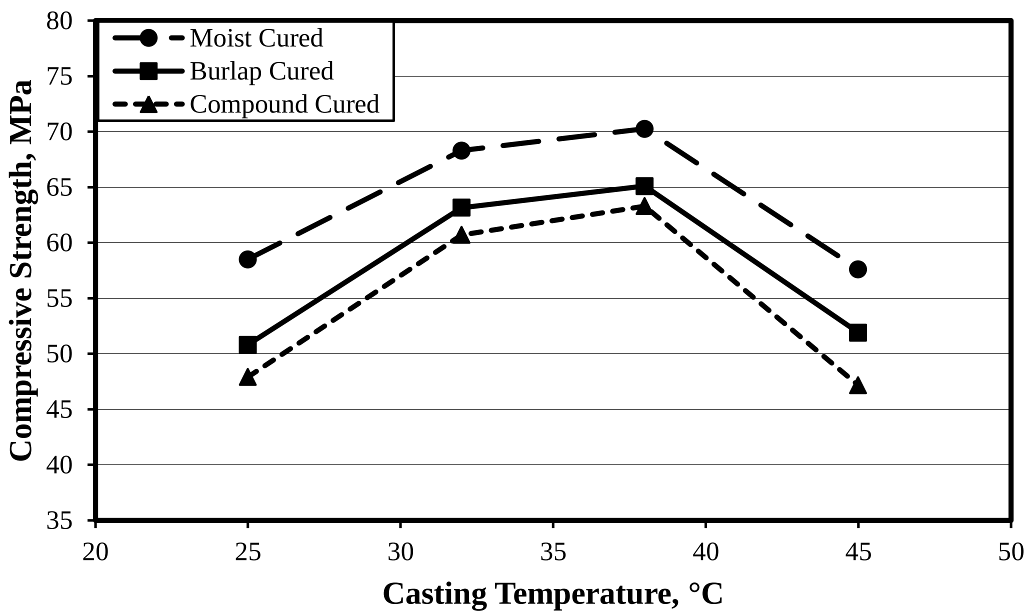

Figure 4.30: Compressive Strength of FA Cement Concretes at 180 Days.

4.1.4 SF Cement Concrete

The effect of partial replacement of OPC by 7% SF on the compressive strength is discussed in this section. For each curing regime, the compressive strength versus age (i.e. curing and/or exposure period) curves were plotted for all the concrete specimens prepared at a constant w/cm ratio of 0.4 and cast at varying temperatures of 25-45°C, as shown in Figures 4.31 through 4.34.

Effect of Curing Period on Compressive Strength of SF Cement Concrete

The compressive strength increased with age in all the concrete specimens. As expected, the early compressive strength raised distinctly and continued to increase gradually at later ages due to the pozzolanic reaction. For all curing regimes and casting temperatures studied, it could be noted that the average ratio of compressive strength of SF cement concrete at 3-day to its 28-day was 0.62, which was significantly more than all the other cementitious materials. This is ascribed to the high reactivity of silica fume as compared to other pozzolanic materials used in this investigation. Further, the ratio of 180-day to 28-day was 1.40. Bentz et al. [108] reported that the early strength development (up to 7 days) of SF cement concrete is possibly due to its filler action that increase the packing efficiency together with improving the interface zone with aggregates. Saber [109] also noticed that the strength gain in SF cement concrete was higher than OPC concrete. He found that the ratio of compressive strength at 7-day to 28-day for OPC concrete was in the range of 0.60-0.86, while this ratio for SF cement concrete was between 0.76 to 0.97.

Effect of Curing Regime on Compressive Strength of SF Cement Concrete

From Tables 4.1 to 4.3, the 28-day compressive strength of the moist cured specimens was on average 8.4 and 14.5% higher than that of the concrete specimens cured by covering with wet burlap and application of a curing compound, respectively. Moreover, the compressive strength of the concrete specimens cured by covering with wet burlap was 5.6% more than that of the concrete specimens cured by applying a curing compound. It is suggested that prolonged moist curing is required for the strength development of SF cement concrete between the ages of 3 to 28 days, which is essential because of its pozzolanic reaction [110].

Effect of Casting Temperature on Compressive Strength of SF Cement Concrete

For all the curing regimes, the compressive strength increased with the rise in casting temperature during early ages of up to 7 days, as shown in Tables 4.1 to 4.3. On average, the 3- and 7-day compressive strength of concrete specimens cast at 45°C was 21.1, 15.0 and 6.7% greater than that of the specimens cast at 25, 32 and 38°C, respectively. Conversely, at later ages of 28 to 180 days, the 32°C was the optimum temperature at which maximum compressive strength was observed in the concrete specimens (alike 100% OPC concrete specimens) followed by those that were cast at 38°C, while the difference between compressive strength of the concrete specimens cast at 25 and 45°C was marginal and relatively low, as shown in Tables 4.1 through 4.3 and depicted in Figures 4.35-4.36. On average, the 28-day compressive strength of the concrete specimens cast at 32°C was 15.1, 3.5 and 18.6% more than that of the concrete specimens cast at 25, 38 or 45°C. Unlike other blending materials, the lower optimum casting temperature of the silica fume concrete is possibly due to its high reactivity, which is ascribed to the glassy (amorphous) form of silica that is highly reactive and having extremely fine particles that speed up the reaction with $Ca(OH)_2$ produced by the hydration of OPC [32].

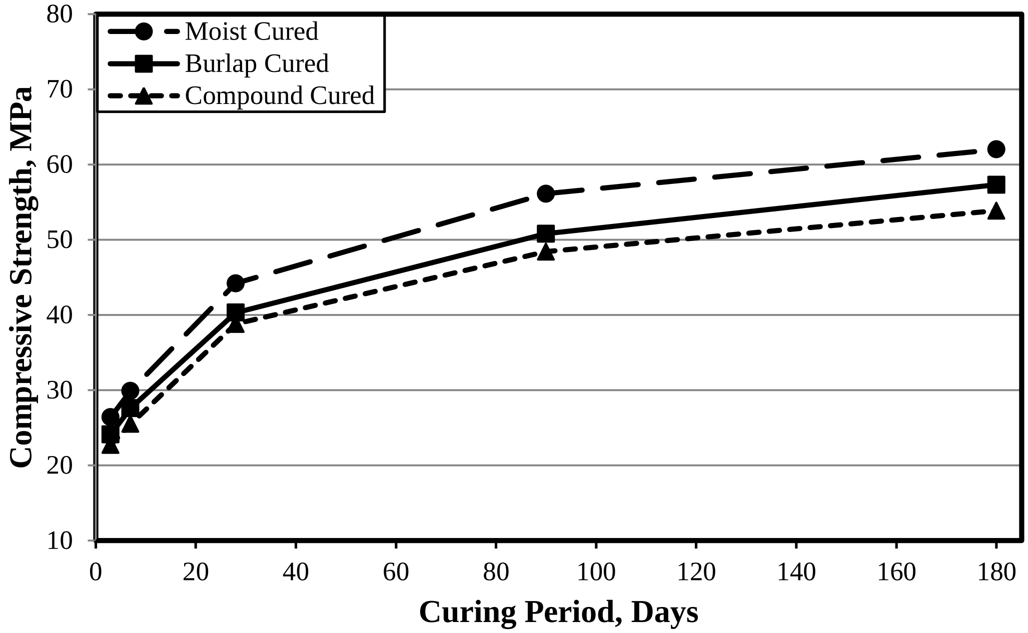

Figure 4.31: Compressive Strength Development of SF Cement Concrete Prepared with w/cm Ratio of 0.4 and Cast at 25°C.

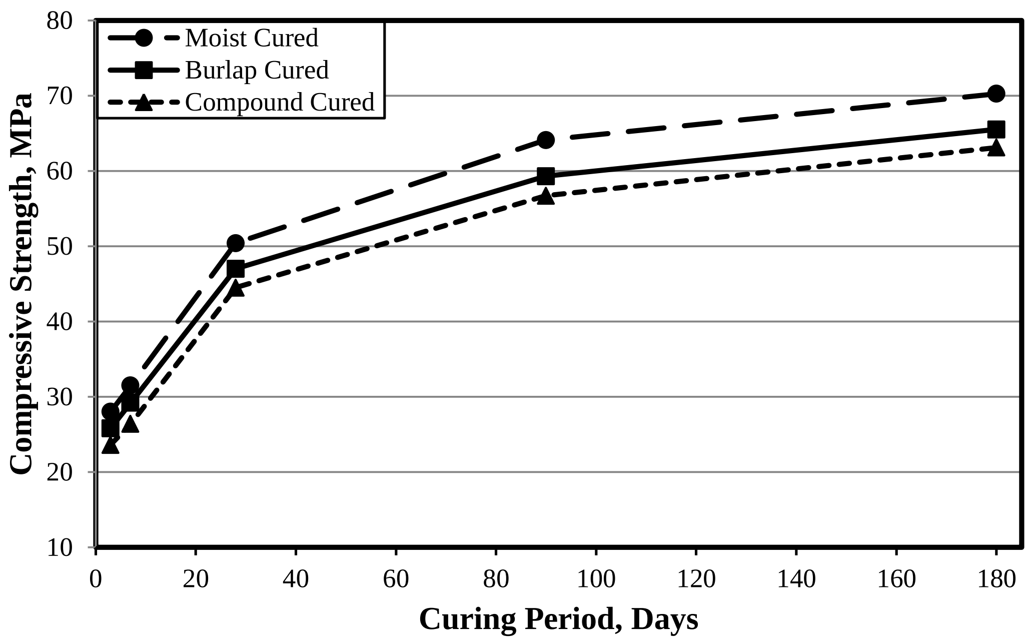

Figure 4.32: Compressive Strength Development of SF Cement Concrete Prepared with w/cm Ratio of 0.4 and Cast at 32°C.

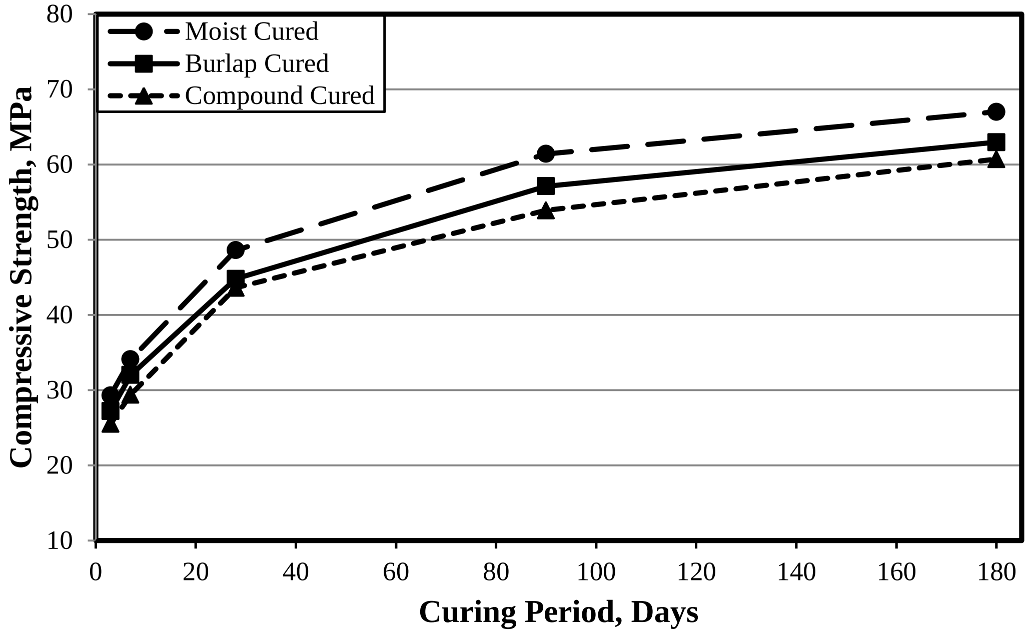

Figure 4.33: Compressive Strength Development of SF Cement Concrete Prepared with w/cm Ratio of 0.4 and Cast at 38°C.

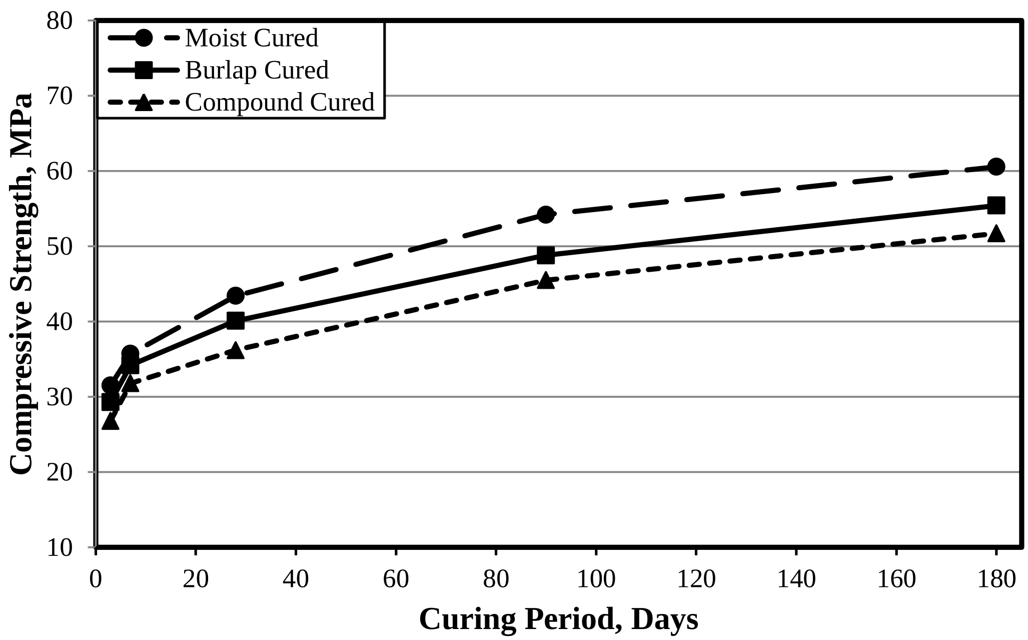

Figure 4.34: Compressive Strength Development of SF Cement Concrete Prepared with w/cm Ratio of 0.4 and Cast at 45°C.

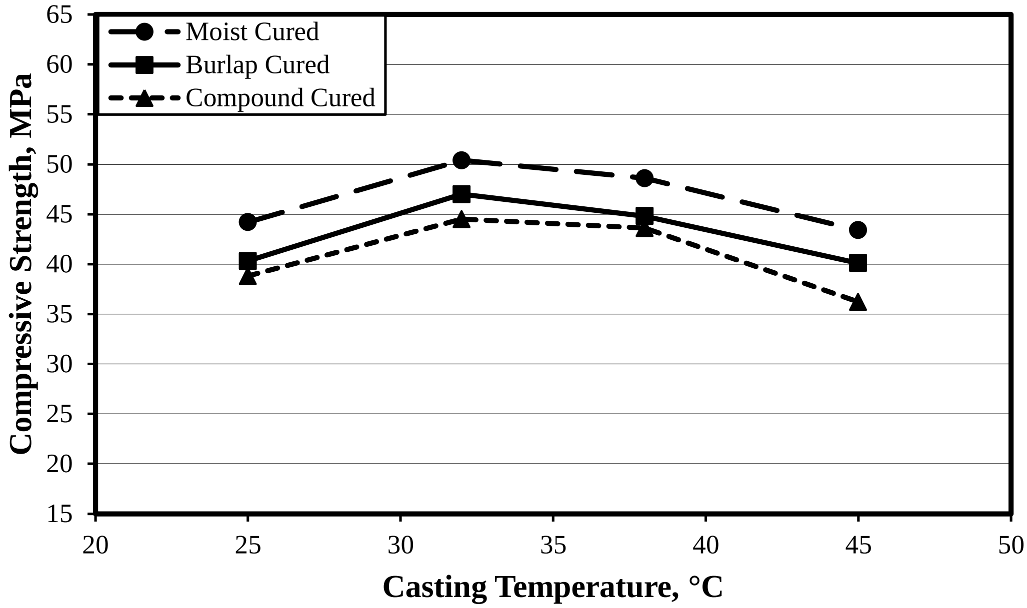

Figure 4.35: Compressive Strength of SF Cement Concretes at 28 Days.

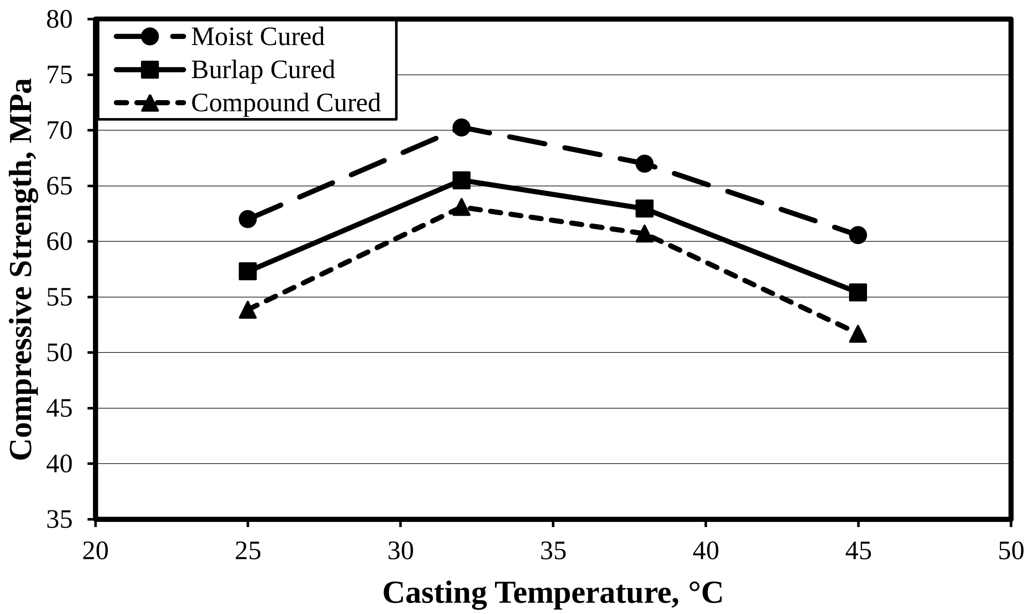

Figure 4.36: Compressive Strength of SF Cement Concretes at 180 Days.

4.1.5 GGBFS Cement Concrete

The compressive strength development of GGBFS cement concrete (OPC + 70% GGBFS) specimens prepared with a w/cm ratio of 0.4, cast at 25, 32, 38 or 45°C and subjected to moist curing, curing by covering with wet burlap or applying a curing compound is depicted in Figures 4.37 through 4.40.

Effect of Curing Period on Compressive Strength of GGBFS Cement Concrete

The compressive strength increased with exposure period in all the concrete specimens. As expected, the increase in compressive strength was slow at early ages due to the high percentage of replacement but the strength developed swiftly at later ages due to the pozzolanic reaction. Regardless of any curing regime and casting temperature assessed, it is noted that the average ratio of compressive strength of GGBFS cement concrete at 3-day to its 28-day was 0.54 while the ratio of 180-day to 28-day was 1.62, which was significantly higher than all the other cementitious materials. Previous study [111] indicated that GGBFS cement concretes tend to minimize the heat of hydration than OPC concretes and, therefore, its early strength gain is also slower. However, at later ages, it may gain more strength than OPC concretes. The highest long-term strength gain in GGBFS concrete is due the progressive alkali emission by the GGBFS cement, along with the calcium hydroxide formation of OPC, resulting in continuous reaction of GGBFS [112]. Austin and Robins [113] reported that there was a significant increase in pulse velocity in GGBFS cement concrete than OPC concrete when cured under moist condition.

Effect of Curing Regime on Compressive Strength of GGBFS Cement Concrete

The 28-day compressive strength of the moist cured specimens was on average 8.4 and 20.8% more than that of the concrete specimens cured by covering with wet burlap or applying a curing compound, respectively, as shown in Tables 4.1 to 4.3. Further, the compressive strength of the concrete specimens cured by covering with wet burlap was higher than that of the concrete specimens cured by applying a curing compound by about 11.5% on average. It was reported that the disadvantage of GGBFS concretes is that they proved to be more sensitive to poor curing than OPC concrete. In this case, both their strength and permeability and, hence, their durability, were seriously impaired if not cured for longer period [58,59].

Effect of Casting Temperature on Compressive Strength of GGBFS Cement Concrete

The compressive strength increased with the increase in casting temperature during early ages of up to 7 days, as shown in Tables 4.1 to 4.3. On average, the 3- and 7-day compressive strength of concrete specimens cast at 45°C was 32.6, 20.4 and 10.4% higher than those specimens cast at 25, 32 and 38°C, respectively. Nevertheless, at later ages of 28 to 180 days, the maximum compressive strength was noted in the concrete specimens cast at 38°C followed by those that were cast at 32 and 25°C, while the compressive strength of the concrete specimens cast at 45°C was the lowest, as shown in Tables 4.1 through 4.3 and depicted in Figures 4.41-4.42. On average, the 28-day compressive strength of the concrete specimens cast at 38°C was 25.4, 14.3 and 33.7% more than that of the concrete specimens cast at 25, 32 or 45°C, respectively. The superior performance of GGBFS as compared to OPC concrete at elevated temperature is reported by many authors. Austin et al. [58] found that neat OPC concrete specimens performed better in temperate climatic conditions (16-20°C), whereas 50% GGBFS cement concretes were effective in hot weather condition (12 hr. cycles of temperature about 10 and 45°C), in terms of compressive strength, pulse velocity and permeability using different curing methods. Roy and Idorn [114] also reported the beneficial effect of increased temperature on GGBFS cement concrete.

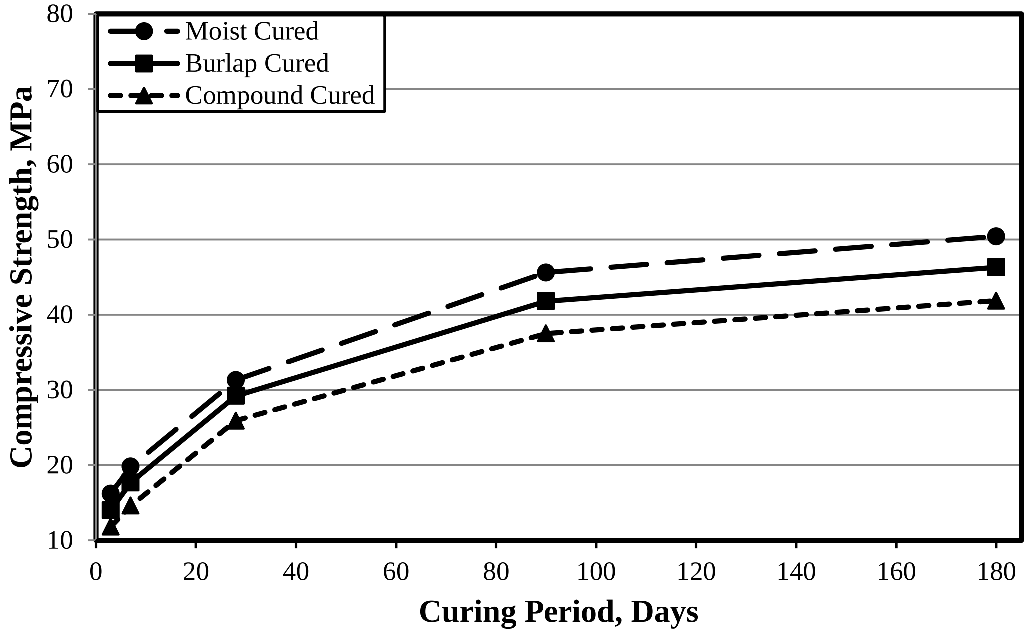

Figure 4.37: Compressive Strength Development of GGBFS Cement Concrete Prepared with w/cm Ratio of 0.4 and Cast at 25°C.

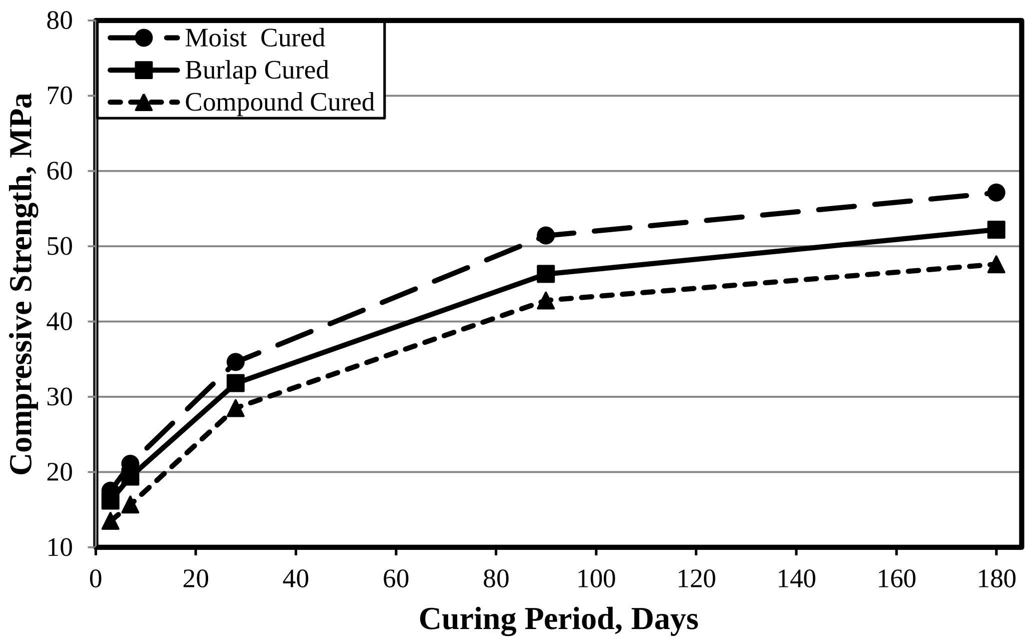

Figure 4.38: Compressive Strength Development of GGBFS Cement Concrete Prepared with w/cm Ratio of 0.4 and Cast at 32°C.

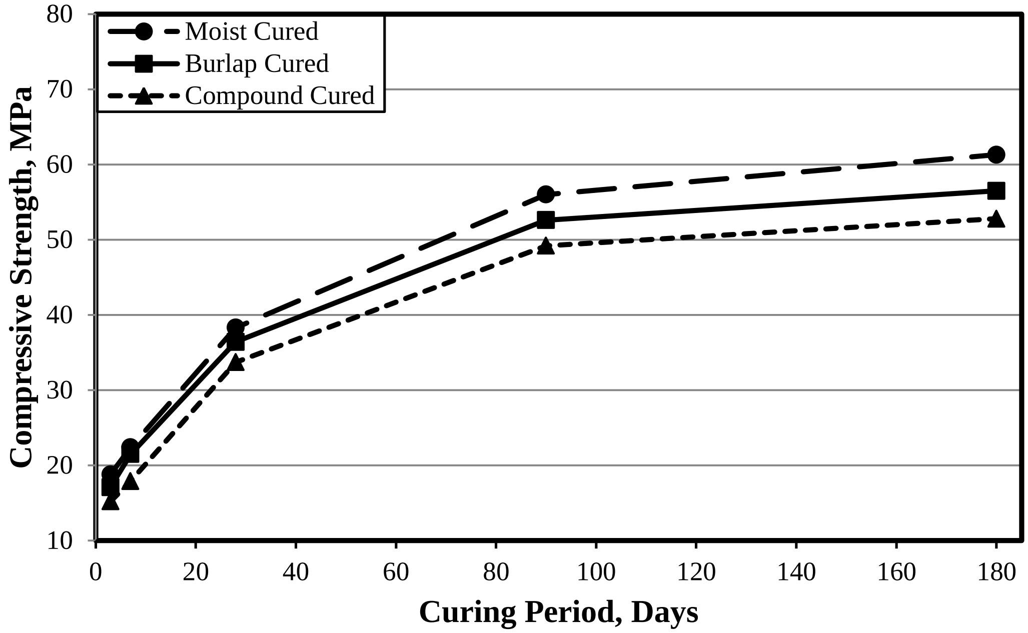

Figure 4.39: Compressive Strength Development of GGBFS Cement Concrete Prepared with w/cm Ratio of 0.4 and Cast at 38°C.

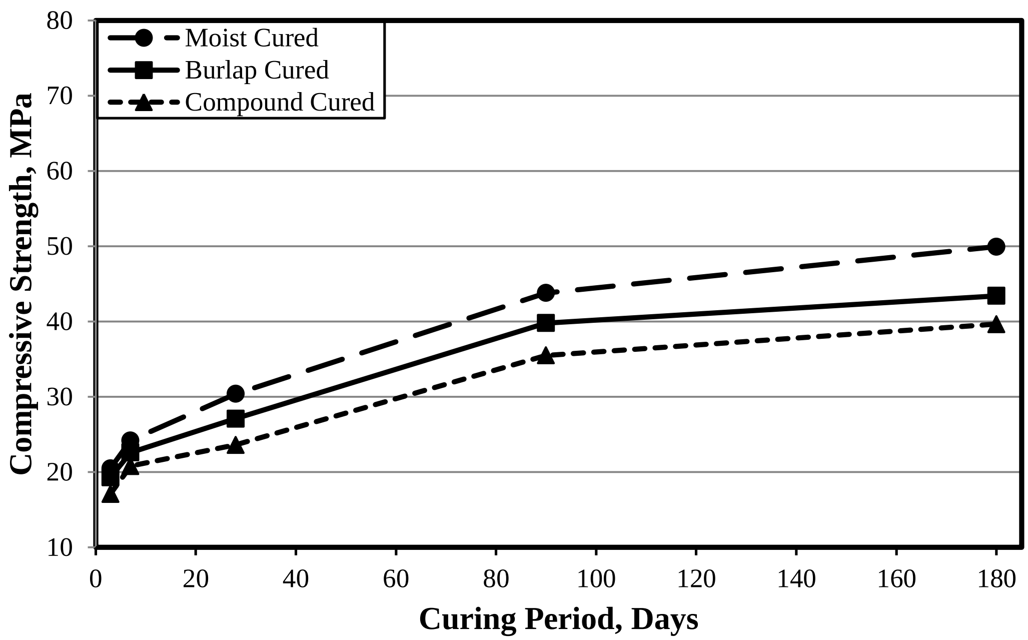

Figure 4.40: Compressive Strength Development of GGBFS Cement Concrete Prepared with w/cm Ratio of 0.4 and Cast at 45°C.

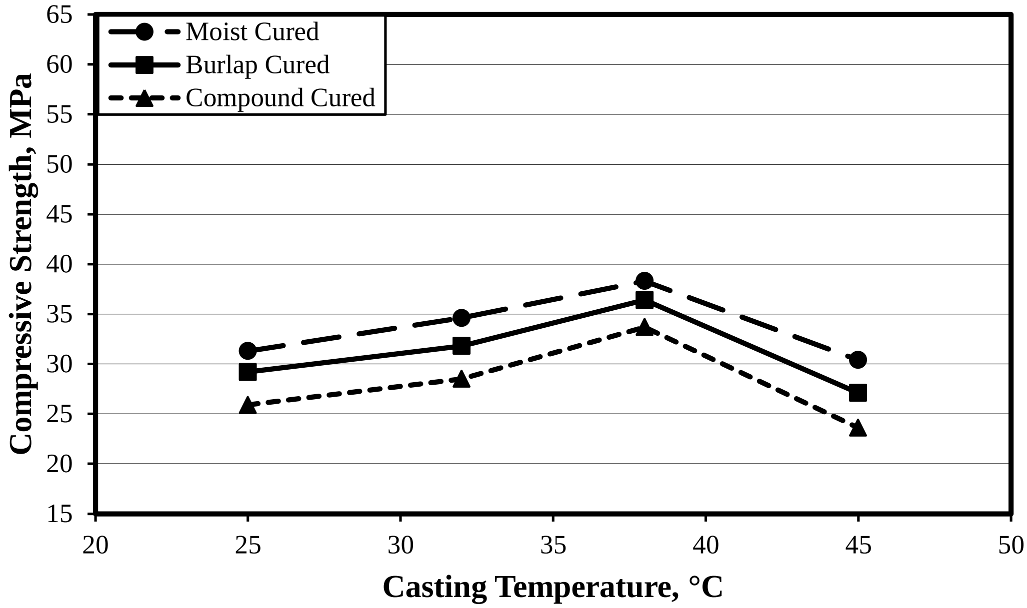

Figure 4.41: Compressive Strength of GGBFS Cement Concretes at 28 Days.

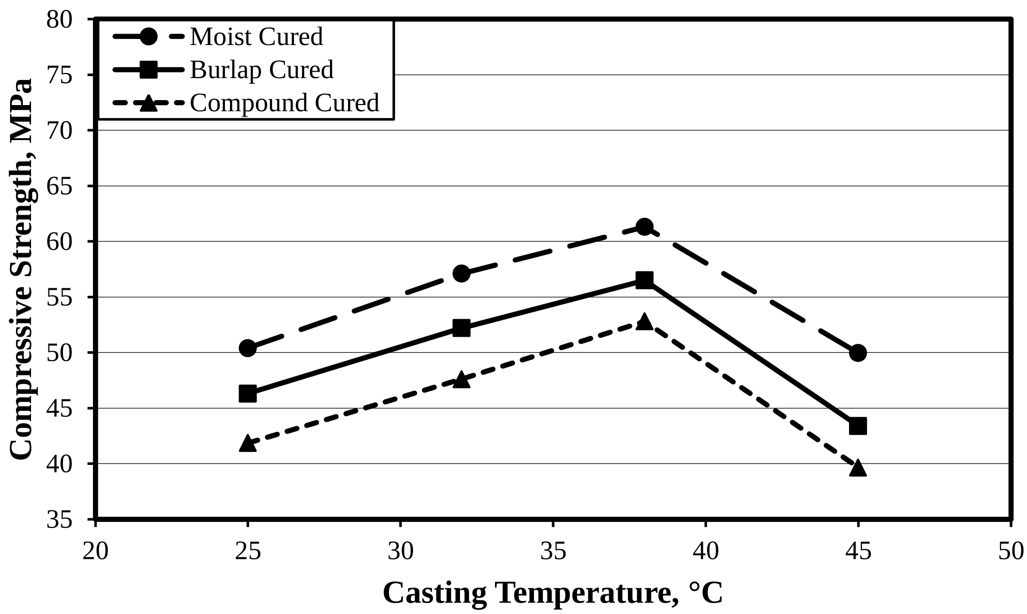

Figure 4.42: Compressive Strength of GGBFS Cement Concretes at 180 Days.

4.1.6 NP Cement Concrete

The effect of partial replacement of OPC by 20% NP cement on the compressive strength is discussed in this section. For each curing regime, the compressive strength versus age (i.e. curing and/or exposure period) curves were plotted for all the concrete specimens prepared at a constant w/cm ratio of 0.4 and cast at range of temperatures of 25-45°C, as shown in Figures 4.43 through 4.46.

Effect of Curing Period on Compressive Strength of NP Cement Concrete

The compressive strength increased with the curing period in all the concrete specimens. As expected, the compressive strength increased gradually during early ages while strength gain was moderate at later ages due to the pozzolanic reaction. For all curing regimes and casting temperatures examined, it is noted that the average ratio of compressive strength of NP cement concrete at 3-day to its 28-day was 0.54, which is equivalent to VFFA and GGBFS cement concretes. However the ratio of 180-day to 28-day was 1.50, which was comparable to FA cement concretes and shows significantly higher improvement in strength after GGBFS cement concrete specimens. Najimi et al. [94] reported that due to the lower content of amorphous silica in natural pozzolan, its hydration rate was slow. Hence, the best mechanical and durability properties of these concrete were obtained after 90 and 180 days of curing.

Effect of Curing Regime on Compressive Strength of NP Cement Concrete

From Tables 4.1 to 4.3, the 28-day compressive strength of the moist cured specimens was on average 5.8 and 14.3% greater than that of the concrete specimens cured by covering with wet burlap or applying a curing compound, respectively. Similarly, the compressive strength of the concrete specimens cured by covering with wet burlap was

8.1% more than that of the concrete specimens cured by application of a curing compound. Although longer periods of initial curing are essential for concretes in hot weather, especially for concretes containing natural pozzolan, a period of more than seven days was found necessary [60].

Effect of Casting Temperature on Compressive Strength of NP Cement Concrete

At the ages of 3 and 7 days, the compressive strength increased with increment in casting temperature, as shown in Tables 4.1 to 4.3. On average, the 3- and 7-day compressive strength of concrete specimens cast at 45°C was 23.2, 10.3 and 5.4% more than that of the specimens cast at 25, 32 and 38°C, respectively. On the other hand, at later ages of 28 to 180 days, the maximum compressive strength was measured in the concrete specimens cast at 38°C followed by those that were cast at 32 or 45°C, while the compressive strength of the concrete specimens cast at 25°C was the lowest, as shown in Tables 4.1 through 4.3 and depicted in Figures 4.47-4.48. On average, the 28-day compressive strength of the concrete specimens cast at 38°C was 18.8, 6.2 and 12.3% more than that of the concrete specimens cast at 25, 32 or 45°C, respectively.

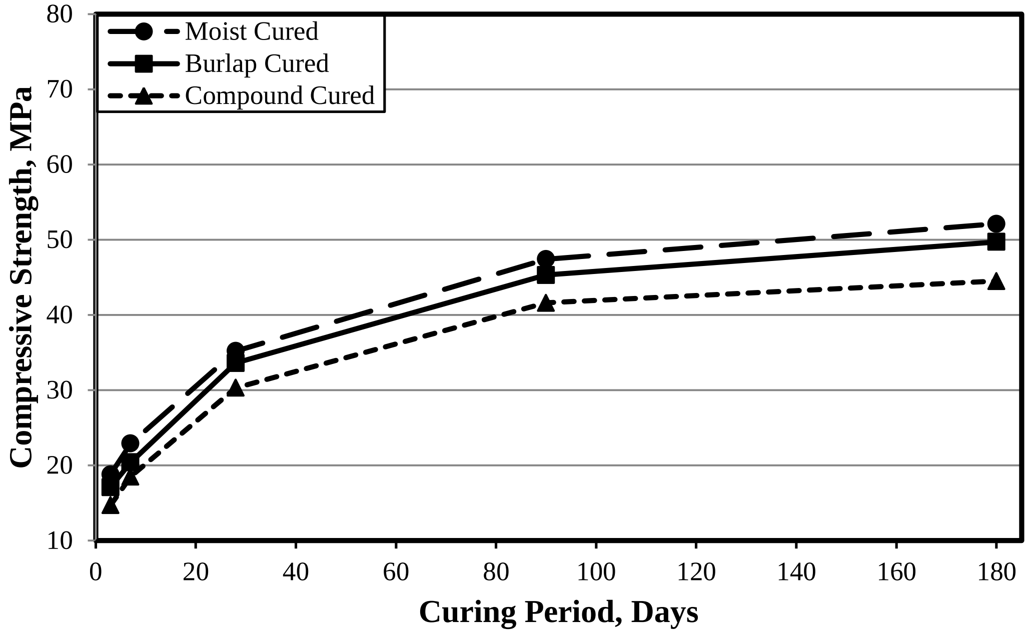

Figure 4.43: Compressive Strength Development of NP Cement Concrete Prepared with w/cm Ratio of 0.4 and Cast at 25°C.

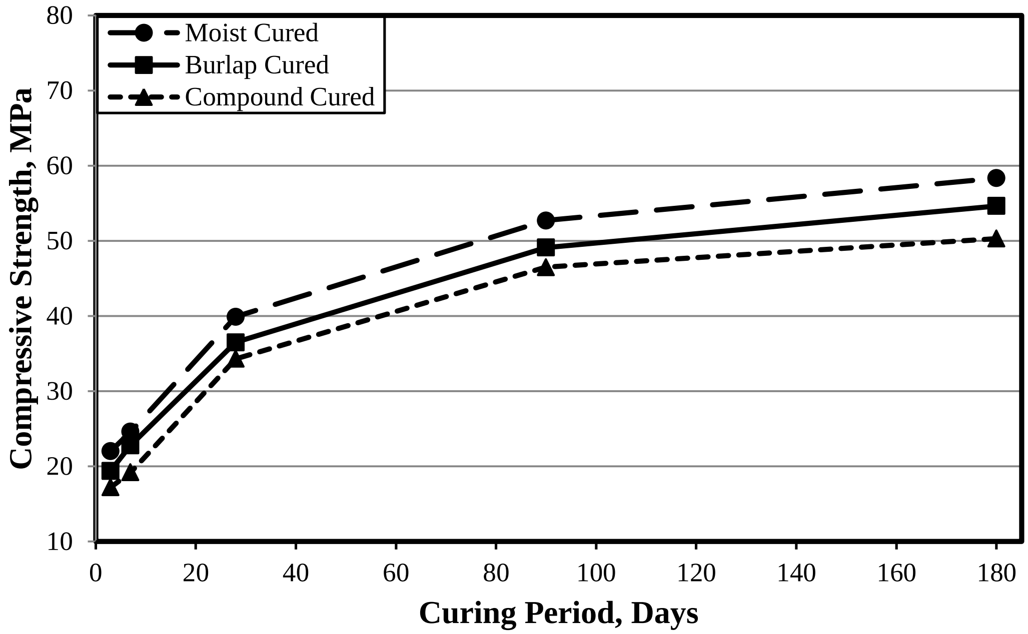

Figure 4.44: Compressive Strength Development of NP Cement Concrete Prepared with w/cm Ratio of 0.4 and Cast at 32°C.

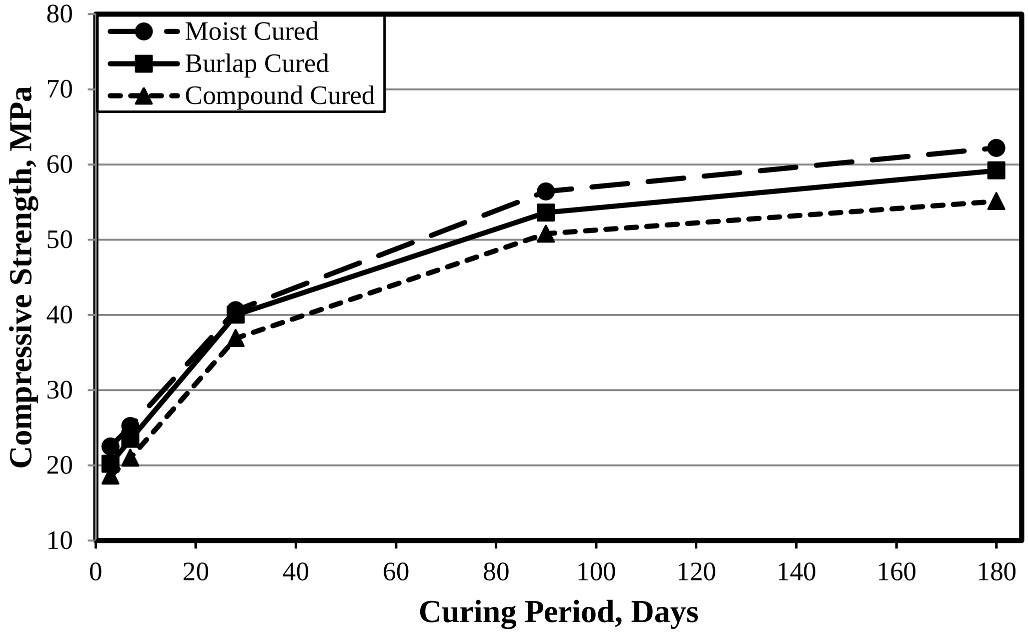

Figure 4.45: Compressive Strength Development of NP Cement Concrete Prepared with w/cm Ratio of 0.4 and Cast at 38°C.

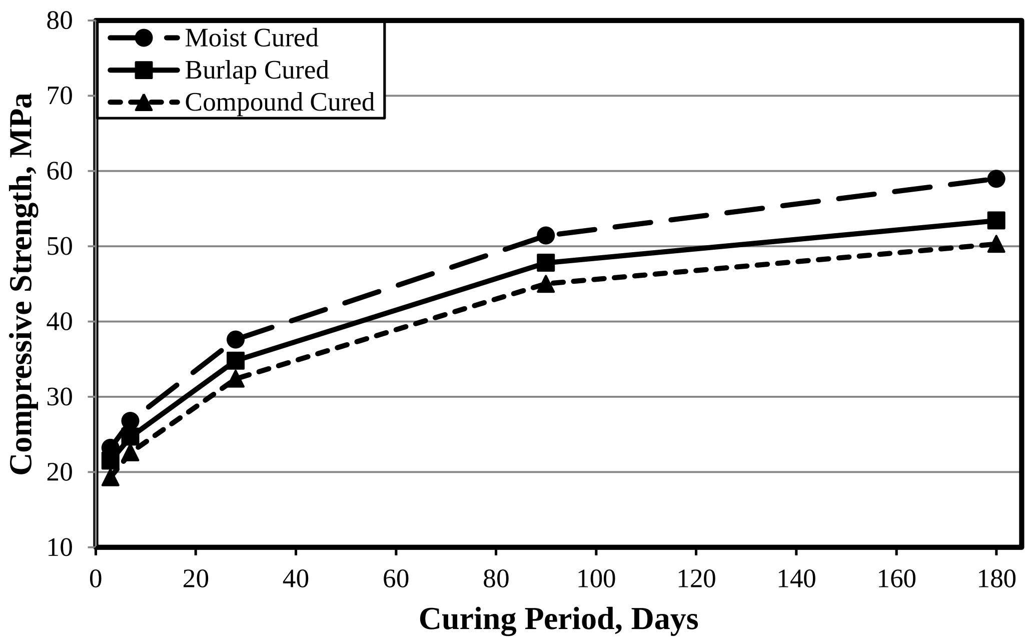

Figure 4.46: Compressive Strength Development of NP Cement Concrete Prepared with w/cm Ratio of 0.4 and Cast at 45°C.

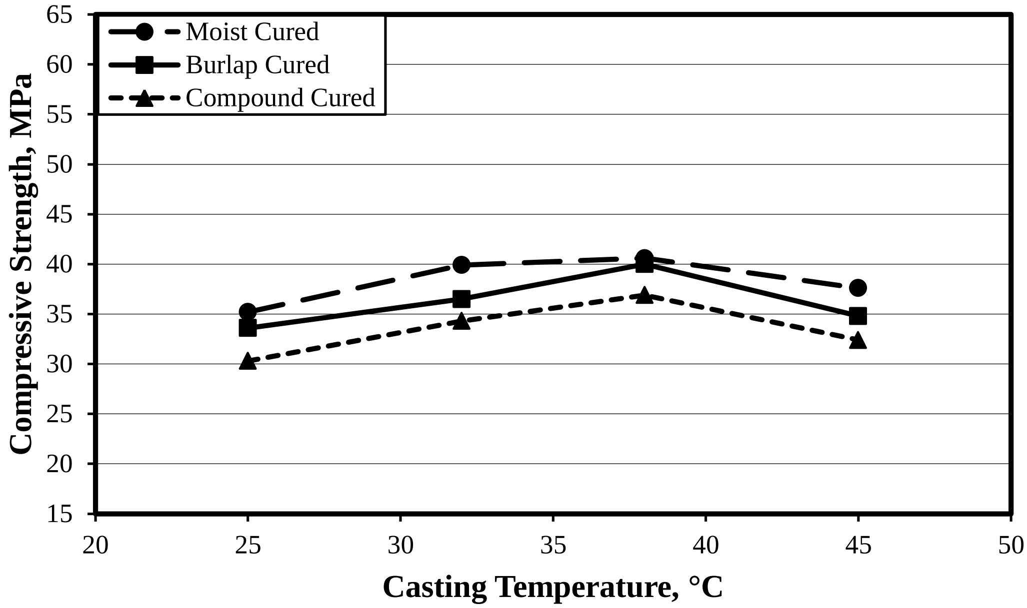

Figure 4.47: Compressive Strength of NP Cement Concretes at 28 Days.

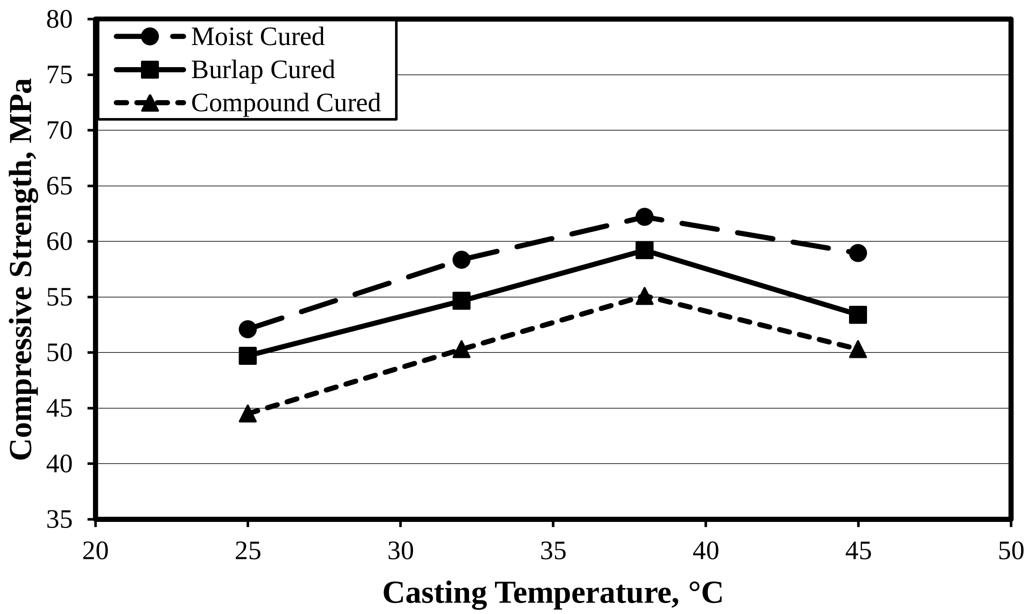

Figure 4.48: Compressive Strength of NP Cement Concretes at 180 Days.

4.1.7 Comparison of Compressive Strength of Cementitious Materials

Figures 4.49 through 4.54 depict the 28- and 180-day compressive strength of plain and blended cement concrete specimens prepared with a constant w/cm ratio of 0.4, cast at 25 to 45°C and cured under moist condition, covering with wet burlap or applying a curing compound. As discussed earlier, irrespective of the curing technique utilized, the compressive strength increased up to 32°C. However, a further increase in the casting temperature decreased the compressive strength. An exception to this trend was noted in FA, VFFA, NP and GGBFS blended cement concretes. In these concretes, the compressive strength continued to increase up to a temperature of 38°C; thereafter, there was a decrease in the compressive strength.

Among all cementitious materials, it was also noted from those figures that regardless of any curing condition and casting temperature utilized at 28 days, the maximum value of compressive strength was observed in the SF cement concrete specimens cast at 25 or 32°C, while the maximum value of compressive strength was noted in both SF and VFFA cement concrete specimens cast at 38°C. However, VFFA cement concrete specimens attained the maximum strength at casting temperature of 45°C. The minimum compressive strength was measured in GGBFS cement concrete specimens at all casting temperatures at 28-day, which may be due to high percentage of replacement but the strength development was higher that OPC concretes at 38°C. The initial increase in the compressive strength of all cementitious materials may be attributed to the increase in the hydration reaction while the decrease in the compressive strength, with increasing temperature, may be the result of the formation of micro cracks in the concrete due to the evaporation of water and insufficient hydration. Further, the better concrete performance at the casting temperature of 32 or 38°C may be attributed to the close ambient air temperature of about 38°C at the time of casting all concrete mixes. Ortiz et al. [70] also reported that the best mechanical performance of concrete, under hot weather conditions, took place when there was a minimum difference between concrete temperature and ambient temperature.

From the data in Table 4.5, irrespective of casting temperature and curing regime, it could be noted that the ratio of 28-day compressive strength of SF and VFFA cement concretes was comparable to each other, which was on average about 11% higher than OPC concrete. Further, the compressive strength of GGBFS and NP cement concrete was respectively, about 21 and 7% lower than OPC concrete. However, the ratio of the strength of FA to OPC concrete was equal. Similarly, at the age of 180 days, the compressive strength of SF, VFFA, FA and NP cement concrete was 15, 14, 11 and 2% more than OPC concrete, respectively, whereas the ratio of the strength of GGBFS to OPC concrete was 0.94. This difference in the rate of strength development may be attributed to the changes in the microstructure of the concrete prepared using different cementitious materials with time. Al-Amoudi et at. [91] also observed almost same ratio of the compressive strength of SF to OPC and FA to OPC i.e. 1.08 and 0.92, respectively, after 28-day water curing. Further, Al-Gahtani [7] found that such average ratio of VFFA, SF and FA cement concrete to OPC concrete was on average 1.03, 1.15 and 1.12, respectively, after 28-day application of water-based curing compound or covering with wet burlap, which are comparable to the results reported in this study.

The greater compressive strength of the supplementary cementitious materials particularly SF, VFFA and FA cement concretes relative to OPC concrete, indicated its remarkable efficiency when used at the same workability. Such superior performance of these blended cementing materials is also reported by Al-Amoudi et al. [49]. The improvement in strength of FA cement concrete is not only due to its pozzolanicity but also the consequence of its fine particle sizes that fill the pores between cement grains [115]. With the passage of time, the unreacted particles of FA form hydration products and precipitate within the capillary pores resulting in reduced capillary porosity and a dense pore structure [33]. High strength and low permeability in SF cement concretes is the consequence of high fineness of SF cement that reduces bleeding so that no bleed water is trapped under aggregate particles and thus porosity in the interface zone is minimized [32]. As compared to OPC concrete, the lower pulse velocity in GGBFS containing specimens at different percentage level and at all ages of up to 180 days after 28-day water curing was also measured by Shariq et al. [59].

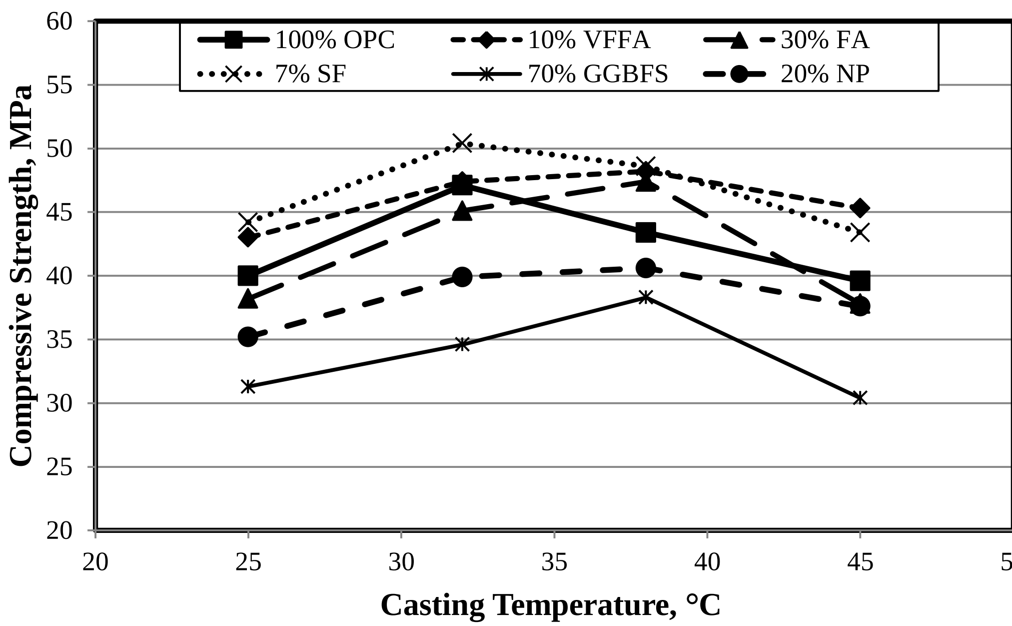

Figure 4.49: Compressive Strength of OPC and Blended Cement Concretes Prepared with w/cm Ratio of 0.4 and Cast at 25-45°C after 28 Days of Moist Curing.

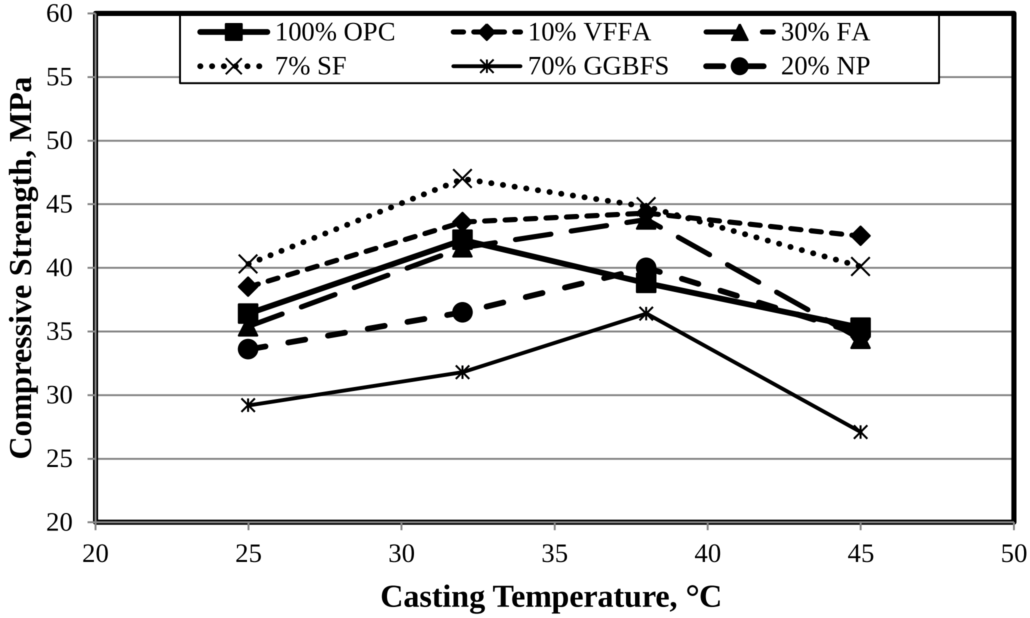

Figure 4.50: Compressive Strength of OPC and Blended Cement Concretes Prepared with w/cm Ratio of 0.4 and Cast at 25-45°C after 28 Days of Curing by Covering with Wet Burlap.

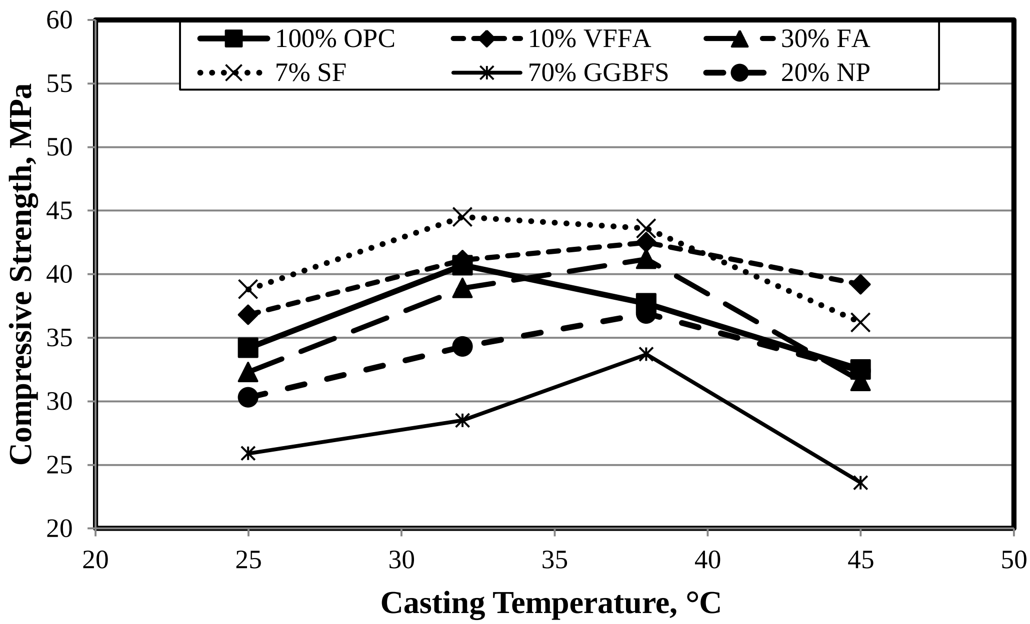

Figure 4.51: Compressive Strength of OPC and Blended Cement Concretes Prepared with w/cm Ratio of 0.4 and Cast at 25-45°C after 28 Days of Applying a Curing Compound.

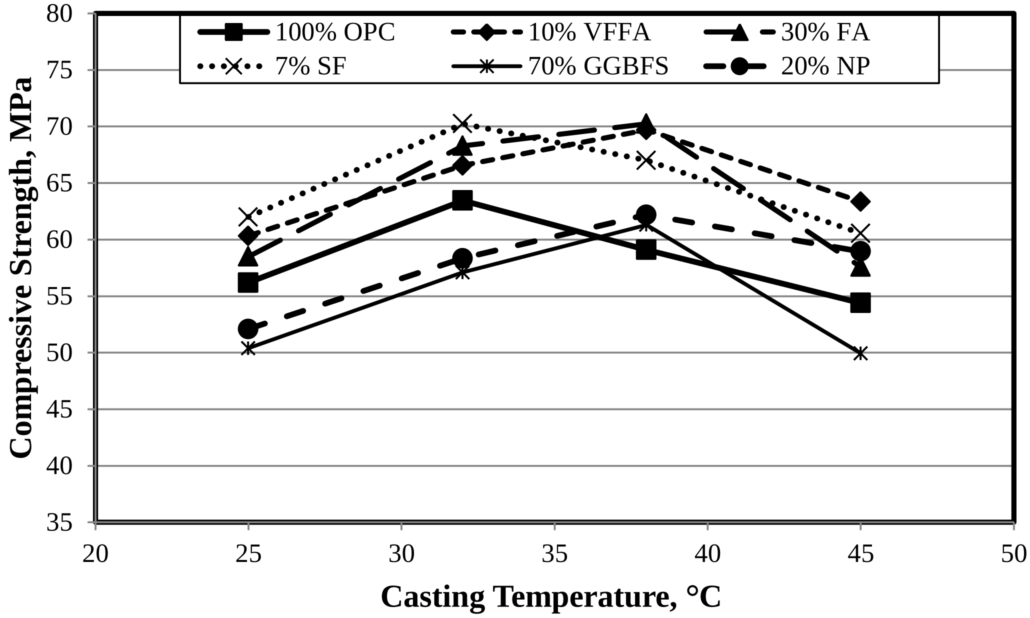

Figure 4.52: Compressive Strength of OPC and Blended Cement Concretes Prepared with w/cm Ratio of 0.4 and Cast at 25-45°C after 180 Days of Moist Curing.

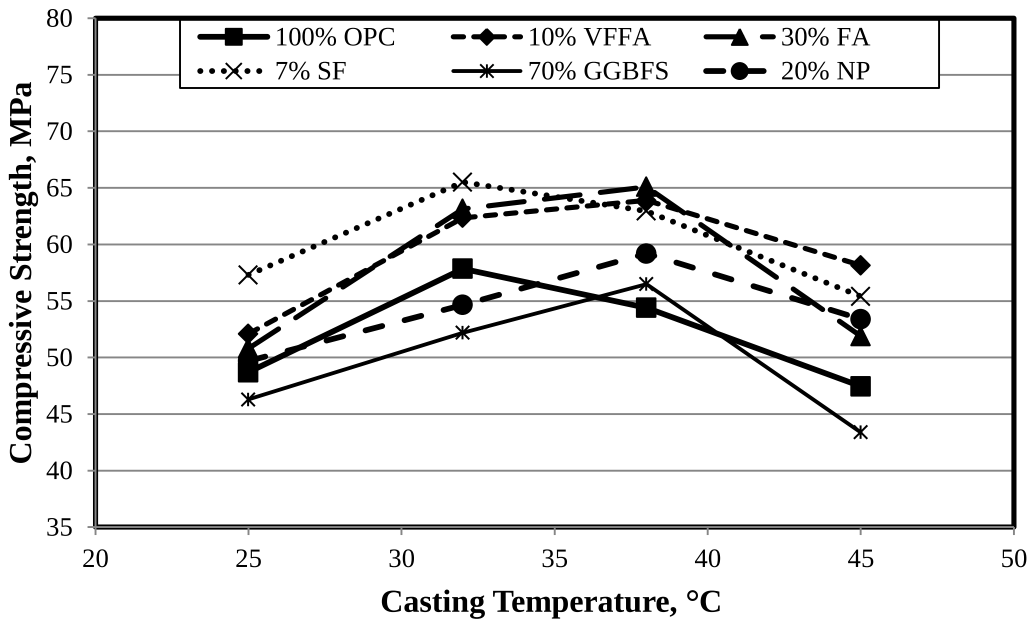

Figure 4.53: Compressive Strength of OPC and Blended Cement Concretes Prepared with w/cm Ratio of 0.4 and Cast at 25-45°C after 180 Days of Curing by Covering with Wet Burlap.

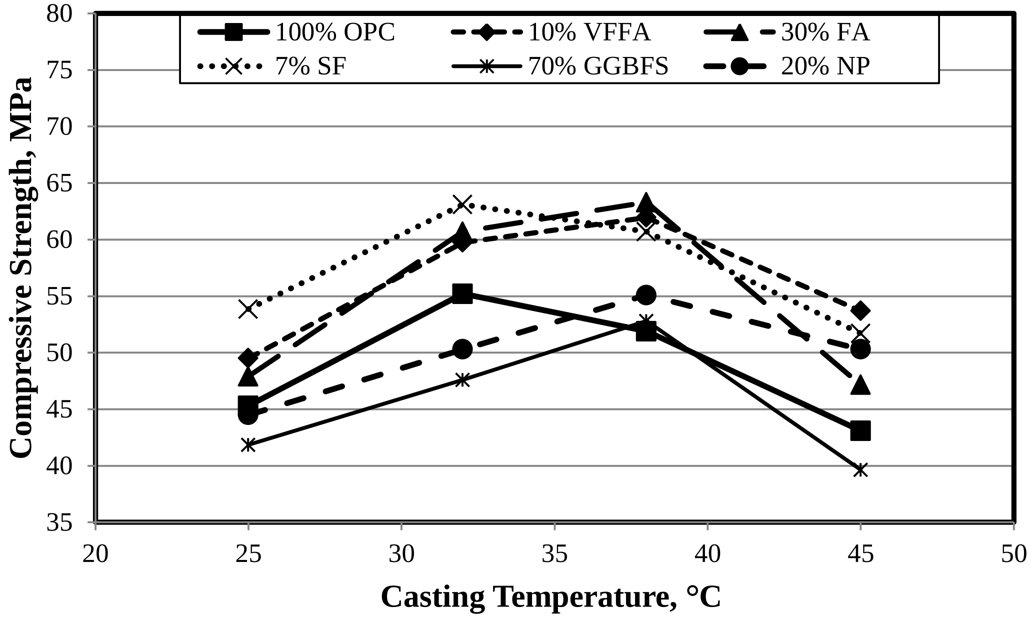

Figure 4.54: Compressive Strength of OPC and Blended Cement Concretes Prepared with w/cm Ratio of 0.4 and Cast at 25-45°C after 180 Days of Applying a Curing Compound.

4.2 Split Tensile Strength

The average split tensile strength of OPC and blended cement concrete specimens, prepared with a w/cm ratio of 0.3, 0.4 or 0.45, cast at 25, 32, 38 or 45°C and tested after 3, 7, 28, 90 and 180 days of curing under moist condition, covering with wet burlap or applying a curing compound is presented in Tables 4.6 to 4.8. Moreover, the data listed in Table 4.9 summarize the split tensile strength development of all kinds of concretes compared to its 28-day strength. Further, quantitative analysis of the split tensile strength of all types of concretes was conducted in Table 4.10, where the split tensile strength of each cementitious materials is expressed as a fraction of the corresponding strength of OPC concrete. As expected, the same trend was noticed in both the compressive and split tensile strength tests and therefore, the effect of curing period, curing regime, casting temperature or w/c ratio on split tensile strength was similar to those on the compressive strength of all the cementitious materials. Additionally, a correlation between the compressive and split tensile strength is developed under Section 4.7.

Table 4.6: Split Tensile Strength of OPC and Blended Cement Concretes Cured by Water Ponding.

Mix No.	Cementitious Materials	w/c Ratio	Casting Temp. (°C)	Split Tensile Strength (MPa)				
				3 Days	7 Days	28 Days	90 Days	180 Days
1	100% OPC	0.3	25	2.59	2.97	3.58	4.06	4.41
2	100% OPC	0.3	32	2.72	3.09	3.81	4.28	4.65
3	100% OPC	0.3	38	2.77	3.12	3.73	4.22	4.58
4	100% OPC	0.3	45	3.08	3.26	3.66	4.13	4.41
5	100% OPC	0.4	25	2.36	2.60	3.08	3.72	3.99
6	100% OPC	0.4	32	2.43	2.65	3.50	3.96	4.28
7	100% OPC	0.4	38	2.61	2.83	3.39	3.73	4.04
8	100% OPC	0.4	45	2.74	3.09	3.22	3.64	3.86
9	100% OPC	0.45	25	2.07	2.32	2.88	3.48	3.70
10	100% OPC	0.45	32	2.23	2.40	3.29	3.73	4.02
11	100% OPC	0.45	38	2.31	2.66	3.23	3.68	3.89
12	100% OPC	0.45	45	2.55	2.73	3.04	3.42	3.67
13	OPC + 10% VFFA	0.4	25	2.37	2.60	3.18	3.85	4.14
14	OPC + 10% VFFA	0.4	32	2.52	2.64	3.56	3.96	4.34
15	OPC + 10% VFFA	0.4	38	2.57	2.75	3.62	4.07	4.42
16	OPC + 10% VFFA	0.4	45	2.65	2.98	3.50	3.89	4.24
17	OPC + 30% FA	0.4	25	2.09	2.32	2.93	3.75	4.03
18	OPC + 30% FA	0.4	32	2.15	2.34	3.21	4.05	4.42
19	OPC + 30% FA	0.4	38	2.34	2.58	3.33	4.13	4.50
20	OPC + 30% FA	0.4	45	2.39	2.61	2.77	3.69	3.92
21	OPC + 7% SF	0.4	25	2.56	2.79	3.39	3.99	4.15
22	OPC + 7% SF	0.4	32	2.56	2.84	3.62	4.13	4.62
23	OPC + 7% SF	0.4	38	2.64	2.94	3.50	4.08	4.54
24	OPC + 7% SF	0.4	45	2.81	3.15	3.37	3.74	4.02
25	OPC + 70% GGBFS	0.4	25	1.64	2.04	2.53	3.30	3.62
26	OPC + 70% GGBFS	0.4	32	1.69	2.10	2.76	3.50	3.85
27	OPC + 70% GGBFS	0.4	38	2.03	2.25	2.98	3.82	4.24
28	OPC + 70% GGBFS	0.4	45	2.15	2.24	2.42	3.14	3.47
29	OPC + 20% NP	0.4	25	1.80	2.11	2.86	3.36	3.75
30	OPC + 20% NP	0.4	32	1.94	2.18	2.98	3.57	3.86
31	OPC + 20% NP	0.4	38	2.03	2.25	3.18	3.90	4.35
32	OPC + 20% NP	0.4	45	2.10	2.53	2.87	3.72	4.03

Table 4.7: Split Tensile Strength of OPC and Blended Cement Concretes Cured by Covering with Wet Burlap.

Mix No.	Cementitious Materials	w/c Ratio	Casting Temp. (°C)	Split Tensile Strength (MPa)				
				3 Days	7 Days	28 Days	90 Days	180 Days
1	100% OPC	0.3	25	2.50	2.86	3.35	3.66	4.19
2	100% OPC	0.3	32	2.56	2.91	3.72	4.06	4.31
3	100% OPC	0.3	38	2.65	3.03	3.45	4.04	4.27
4	100% OPC	0.3	45	2.95	3.28	3.38	3.92	4.17
5	100% OPC	0.4	25	2.28	2.45	2.98	3.57	3.84
6	100% OPC	0.4	32	2.37	2.55	3.25	3.70	3.93
7	100% OPC	0.4	38	2.57	2.68	3.22	3.61	3.87
8	100% OPC	0.4	45	2.66	2.83	3.08	3.40	3.63
9	100% OPC	0.45	25	2.06	2.24	2.73	3.43	3.60
10	100% OPC	0.45	32	2.11	2.27	3.02	3.48	3.73
11	100% OPC	0.45	38	2.25	2.44	2.95	3.38	3.65
12	100% OPC	0.45	45	2.41	2.70	2.91	3.34	3.56
13	OPC + 10% VFFA	0.4	25	2.03	2.32	3.16	3.64	3.92
14	OPC + 10% VFFA	0.4	32	2.40	2.56	3.39	3.78	4.08
15	OPC + 10% VFFA	0.4	38	2.43	2.60	3.48	3.81	4.23
16	OPC + 10% VFFA	0.4	45	2.50	2.83	3.31	3.65	4.00
17	OPC + 30% FA	0.4	25	1.91	2.18	2.83	3.62	3.90
18	OPC + 30% FA	0.4	32	1.97	2.21	2.91	3.78	4.17
19	OPC + 30% FA	0.4	38	2.14	2.47	3.10	3.99	4.36
20	OPC + 30% FA	0.4	45	2.30	2.50	2.62	3.53	3.77
21	OPC + 7% SF	0.4	25	2.35	2.61	3.17	3.67	4.08
22	OPC + 7% SF	0.4	32	2.44	2.68	3.51	3.85	4.40
23	OPC + 7% SF	0.4	38	2.48	2.81	3.31	3.74	4.31
24	OPC + 7% SF	0.4	45	2.68	3.01	3.15	3.60	3.86
25	OPC + 70% GGBFS	0.4	25	1.49	1.95	2.45	2.96	3.37
26	OPC + 70% GGBFS	0.4	32	1.59	1.97	2.66	3.17	3.74
27	OPC + 70% GGBFS	0.4	38	1.97	2.12	2.75	3.67	4.03
28	OPC + 70% GGBFS	0.4	45	2.02	2.12	2.30	2.88	3.24
29	OPC + 20% NP	0.4	25	1.57	2.05	2.56	3.07	3.45
30	OPC + 20% NP	0.4	32	1.68	2.09	2.86	3.26	3.73
31	OPC + 20% NP	0.4	38	1.72	2.10	2.92	3.78	4.19
32	OPC + 20% NP	0.4	45	1.78	2.15	2.68	3.64	3.84

Table 4.8: Split Tensile Strength of OPC and Blended Cement Concretes Cured by Applying a Curing Compound.

Mix No.	Cementitious Materials	w/c Ratio	Casting Temp. (°C)	Split Tensile Strength (MPa)				
				3 Days	7 Days	28 Days	90 Days	180 Days
1	100% OPC	0.3	25	2.38	2.74	3.28	3.62	4.10
2	100% OPC	0.3	32	2.53	2.96	3.66	4.01	4.30
3	100% OPC	0.3	38	2.58	2.90	3.36	3.89	4.23
4	100% OPC	0.3	45	2.73	3.15	3.30	3.85	4.05
5	100% OPC	0.4	25	2.25	2.38	2.95	3.45	3.77
6	100% OPC	0.4	32	2.30	2.48	3.16	3.55	3.82
7	100% OPC	0.4	38	2.30	2.59	3.19	3.50	3.79
8	100% OPC	0.4	45	2.41	2.75	2.86	3.29	3.52
9	100% OPC	0.45	25	1.80	2.12	2.65	3.23	3.45
10	100% OPC	0.45	32	1.95	2.07	2.90	3.39	3.55
11	100% OPC	0.45	38	2.10	2.32	2.87	3.32	3.47
12	100% OPC	0.45	45	2.32	2.55	2.73	3.19	3.31
13	OPC + 10% VFFA	0.4	25	1.91	2.25	3.07	3.46	3.92
14	OPC + 10% VFFA	0.4	32	2.25	2.48	3.23	3.70	4.03
15	OPC + 10% VFFA	0.4	38	2.28	2.54	3.37	3.71	4.20
16	OPC + 10% VFFA	0.4	45	2.35	2.71	3.16	3.57	3.89
17	OPC + 30% FA	0.4	25	1.73	2.04	2.68	3.46	3.84
18	OPC + 30% FA	0.4	32	1.82	2.01	2.84	3.67	3.91
19	OPC + 30% FA	0.4	38	2.04	2.24	2.91	3.86	4.14
20	OPC + 30% FA	0.4	45	2.05	2.27	2.49	3.17	3.54
21	OPC + 7% SF	0.4	25	2.30	2.54	3.11	3.50	3.96
22	OPC + 7% SF	0.4	32	2.32	2.63	3.43	3.76	4.26
23	OPC + 7% SF	0.4	38	2.33	2.69	3.25	3.58	4.08
24	OPC + 7% SF	0.4	45	2.47	2.76	2.86	3.28	3.63
25	OPC + 70% GGBFS	0.4	25	1.42	1.78	2.36	2.70	3.26
26	OPC + 70% GGBFS	0.4	32	1.52	1.81	2.55	3.08	3.60
27	OPC + 70% GGBFS	0.4	38	1.71	1.92	2.61	3.54	3.86
28	OPC + 70% GGBFS	0.4	45	1.76	1.97	2.17	2.62	3.05
29	OPC + 20% NP	0.4	25	1.44	1.73	2.53	2.90	3.37
30	OPC + 20% NP	0.4	32	1.50	1.79	2.65	3.20	3.40
31	OPC + 20% NP	0.4	38	1.56	1.90	2.81	3.63	3.97
32	OPC + 20% NP	0.4	45	1.69	2.05	2.53	3.40	3.62

Table 4.9: Split Tensile Strength of OPC and Blended Cement Concretes Compared to 28-day Strength - Average of all Curing Regimes.

Mix No.	Cementitious Materials	w/c Ratio	Casting Temp. (°C)	f_t / f_t (28 Days)				
				3 Days	7 Days	28 Days	90 Days	180 Days
1	100% OPC	0.3	25	0.73	0.84	1.00	1.11	1.24
2	100% OPC	0.3	32	0.70	0.80	1.00	1.10	1.18
3	100% OPC	0.3	38	0.76	0.86	1.00	1.15	1.24
4	100% OPC	0.3	45	0.85	0.94	1.00	1.15	1.22
5	100% OPC	0.4	25	0.76	0.82	1.00	1.19	1.29
6	100% OPC	0.4	32	0.72	0.78	1.00	1.13	1.21
7	100% OPC	0.4	38	0.76	0.83	1.00	1.11	1.19
8	100% OPC	0.4	45	0.85	0.95	1.00	1.13	1.20
9	100% OPC	0.45	25	0.72	0.81	1.00	1.23	1.30
10	100% OPC	0.45	32	0.68	0.73	1.00	1.15	1.23
11	100% OPC	0.45	38	0.74	0.82	1.00	1.15	1.22
12	100% OPC	0.45	45	0.84	0.92	1.00	1.15	1.21
Average				**0.76**	**0.84**	**1.00**	**1.15**	**1.23**
13	OPC + 10% VFFA	0.4	25	0.67	0.76	1.00	1.16	1.27
14	OPC + 10% VFFA	0.4	32	0.70	0.75	1.00	1.12	1.22
15	OPC + 10% VFFA	0.4	38	0.70	0.75	1.00	1.11	1.23
16	OPC + 10% VFFA	0.4	45	0.75	0.85	1.00	1.11	1.22
Average				**0.71**	**0.78**	**1.00**	**1.13**	**1.24**
17	OPC + 30% FA	0.4	25	0.68	0.77	1.00	1.28	1.40
18	OPC + 30% FA	0.4	32	0.66	0.73	1.00	1.28	1.39
19	OPC + 30% FA	0.4	38	0.70	0.78	1.00	1.28	1.39
20	OPC + 30% FA	0.4	45	0.85	0.94	1.00	1.32	1.43
Average				**0.72**	**0.81**	**1.00**	**1.29**	**1.40**
21	OPC + 7% SF	0.4	25	0.74	0.82	1.00	1.15	1.26
22	OPC + 7% SF	0.4	32	0.69	0.77	1.00	1.11	1.26
23	OPC + 7% SF	0.4	38	0.74	0.84	1.00	1.13	1.28
24	OPC + 7% SF	0.4	45	0.85	0.95	1.00	1.13	1.23
Average				**0.76**	**0.85**	**1.00**	**1.13**	**1.26**
25	OPC + 70% GGBFS	0.4	25	0.62	0.79	1.00	1.22	1.40
26	OPC + 70% GGBFS	0.4	32	0.60	0.74	1.00	1.22	1.40
27	OPC + 70% GGBFS	0.4	38	0.68	0.75	1.00	1.32	1.46
28	OPC + 70% GGBFS	0.4	45	0.86	0.92	1.00	1.25	1.42
Average				**0.69**	**0.80**	**1.00**	**1.25**	**1.42**
29	OPC + 20% NP	0.4	25	0.60	0.74	1.00	1.17	1.33
30	OPC + 20% NP	0.4	32	0.60	0.71	1.00	1.18	1.29
31	OPC + 20% NP	0.4	38	0.59	0.70	1.00	1.27	1.41
32	OPC + 20% NP	0.4	45	0.69	0.83	1.00	1.33	1.42
Average				**0.62**	**0.75**	**1.00**	**1.24**	**1.36**

Table 4.10: Split Tensile Strength of Blended Cement Concretes Compared to the Tensile Strength of OPC Concrete (0.4 w/c) - Average of all Curing Regimes.

Mix No.	Cementitious Materials	w/c Ratio	Casting Temp. (°C)	f_t (Blended Cement) / f_t (OPC) [2]				
				3 Days	7 Days	28 Days	90 Days	180 Days
13	OPC + 10% VFFA	0.4	25	0.91	0.96	1.04	1.02	1.03
14	OPC + 10% VFFA	0.4	32	1.01	1.00	1.03	1.02	1.04
15	OPC + 10% VFFA	0.4	38	0.97	0.97	1.07	1.07	1.10
16	OPC + 10% VFFA	0.4	45	0.96	0.98	1.09	1.08	1.10
Average				**0.96**	**0.98**	**1.06**	**1.05**	**1.07**
17	OPC + 30% FA	0.4	25	0.83	0.88	0.94	1.01	1.01
18	OPC + 30% FA	0.4	32	0.84	0.85	0.90	1.03	1.04
19	OPC + 30% FA	0.4	38	0.87	0.90	0.95	1.11	1.11
20	OPC + 30% FA	0.4	45	0.86	0.85	0.86	1.01	1.02
Average				**0.85**	**0.87**	**0.91**	**1.04**	**1.05**
21	OPC + 7% SF	0.4	25	1.05	1.07	1.07	1.04	1.05
22	OPC + 7% SF	0.4	32	1.03	1.06	1.07	1.05	1.10
23	OPC + 7% SF	0.4	38	1.00	1.04	1.03	1.05	1.10
24	OPC + 7% SF	0.4	45	1.02	1.03	1.02	1.03	1.05
Average				**1.02**	**1.05**	**1.05**	**1.04**	**1.08**
25	OPC + 70% GGBFS	0.4	25	0.66	0.78	0.81	0.83	0.88
26	OPC + 70% GGBFS	0.4	32	0.68	0.76	0.80	0.87	0.93
27	OPC + 70% GGBFS	0.4	38	0.76	0.77	0.85	1.02	1.04
28	OPC + 70% GGBFS	0.4	45	0.76	0.73	0.75	0.84	0.89
Average				**0.71**	**0.76**	**0.81**	**0.89**	**0.93**
29	OPC + 20% NP	0.4	25	0.70	0.79	0.88	0.87	0.91
30	OPC + 20% NP	0.4	32	0.72	0.79	0.86	0.89	0.91
31	OPC + 20% NP	0.4	38	0.71	0.77	0.91	1.04	1.07
32	OPC + 20% NP	0.4	45	0.71	0.77	0.88	1.04	1.04
Average				**0.71**	**0.78**	**0.88**	**0.96**	**0.98**

[2] Ratio of split tensile strength of blended cement concretes to plain cement concretes.

4.3 Pulse Velocity

The average pulse velocity in OPC and blended cement concrete specimens, prepared with a w/cm ratio of 0.3, 0.4 or 0.45, cast at 25, 32, 38 or 45°C and tested after 3, 7, 28, 90 and 180 days of curing under moist condition, covering with wet burlap or applying a curing compound is presented in Tables 4.11 to 4.13. As expected, the same trend was observed in the compressive and split tensile strength and pulse velocity measurements in terms of curing period, curing regime, casting temperature or w/c ratio. With an exception that the pulse velocity slightly dropped at the age of 180 days, for all the parameters investigated. In addition, a relationship between the compressive strength and pulse velocity is formulated under Section 4.7. Investigations have shown that microcracking occurs not only in normal strength concrete but also in moist cured concrete having water to cement ratio of as low as 0.25, prior to the application of the load on concrete [32]. In contrast to compressive strength a retrogression in pulse velocity was also reported by Al-Amoudi et al. [49] in all the OPC, VFFA, FA and SF cement concrete specimens cured with water, wet burlap or applying curing compound, when exposed to thermal variations (25-70°C). The authors concluded that the pulse velocity declination was due to the detrimental effect of exposure to temperature variation that may form micro-cracking without influencing the compressive strength.

Table 4.11: Pulse Velocity in OPC and Blended Cement Concretes Cured by Water Ponding.

Mix No.	Cementitious Materials	w/c Ratio	Casting Temp. (°C)	Pulse Velocity (m/sec)				
				3 Days	7 Days	28 Days	90 Days	180 Days
1	100% OPC	0.3	25	4310	4350	4470	4530	4510
2	100% OPC	0.3	32	4360	4420	4520	4570	4540
3	100% OPC	0.3	38	4330	4380	4480	4520	4500
4	100% OPC	0.3	45	4320	4360	4470	4510	4490
5	100% OPC	0.4	25	4220	4250	4350	4420	4400
6	100% OPC	0.4	32	4280	4330	4420	4480	4450
7	100% OPC	0.4	38	4260	4300	4370	4430	4400
8	100% OPC	0.4	45	4230	4270	4350	4400	4380
9	100% OPC	0.45	25	4170	4210	4310	4360	4340
10	100% OPC	0.45	32	4210	4260	4370	4430	4400
11	100% OPC	0.45	38	4190	4220	4320	4370	4350
12	100% OPC	0.45	45	4180	4210	4310	4340	4320
13	OPC + 10% VFFA	0.4	25	4190	4230	4360	4440	4400
14	OPC + 10% VFFA	0.4	32	4240	4270	4380	4470	4420
15	OPC + 10% VFFA	0.4	38	4290	4340	4460	4580	4540
16	OPC + 10% VFFA	0.4	45	4270	4330	4450	4550	4510
17	OPC + 30% FA	0.4	25	4170	4200	4320	4430	4390
18	OPC + 30% FA	0.4	32	4260	4300	4370	4480	4430
19	OPC + 30% FA	0.4	38	4320	4360	4450	4600	4550
20	OPC + 30% FA	0.4	45	4190	4220	4320	4410	4380
21	OPC + 7% SF	0.4	25	4280	4330	4460	4550	4500
22	OPC + 7% SF	0.4	32	4350	4410	4530	4630	4590
23	OPC + 7% SF	0.4	38	4310	4360	4480	4570	4520
24	OPC + 7% SF	0.4	45	4290	4350	4460	4530	4490
25	OPC + 70% GGBFS	0.4	25	3820	3850	3930	4060	4030
26	OPC + 70% GGBFS	0.4	32	3910	3950	4040	4160	4120
27	OPC + 70% GGBFS	0.4	38	3980	4030	4120	4250	4210
28	OPC + 70% GGBFS	0.4	45	3860	3890	3950	4070	4040
29	OPC + 20% NP	0.4	25	4110	4160	4240	4350	4320
30	OPC + 20% NP	0.4	32	4190	4230	4330	4420	4380
31	OPC + 20% NP	0.4	38	4250	4280	4380	4460	4430
32	OPC + 20% NP	0.4	45	4220	4250	4340	4420	4390

Table 4.12: Pulse Velocity in OPC and Blended Cement Concretes Cured by Covering with Wet Burlap.

Mix No.	Cementitious Materials	w/c Ratio	Casting Temp. (°C)	Pulse Velocity (m/sec)				
				3 Days	7 Days	28 Days	90 Days	180 Days
1	100% OPC	0.3	25	4270	4300	4400	4450	4420
2	100% OPC	0.3	32	4320	4360	4440	4500	4470
3	100% OPC	0.3	38	4300	4350	4440	4490	4460
4	100% OPC	0.3	45	4280	4330	4390	4430	4400
5	100% OPC	0.4	25	4190	4210	4290	4340	4310
6	100% OPC	0.4	32	4240	4280	4380	4420	4390
7	100% OPC	0.4	38	4220	4250	4340	4380	4350
8	100% OPC	0.4	45	4210	4230	4300	4340	4320
9	100% OPC	0.45	25	4130	4170	4260	4300	4270
10	100% OPC	0.45	32	4170	4200	4280	4340	4310
11	100% OPC	0.45	38	4160	4190	4270	4310	4280
12	100% OPC	0.45	45	4150	4180	4250	4290	4270
13	OPC + 10% VFFA	0.4	25	4170	4200	4320	4380	4330
14	OPC + 10% VFFA	0.4	32	4210	4250	4360	4430	4380
15	OPC + 10% VFFA	0.4	38	4250	4300	4410	4510	4440
16	OPC + 10% VFFA	0.4	45	4250	4290	4400	4480	4430
17	OPC + 30% FA	0.4	25	4160	4180	4280	4360	4320
18	OPC + 30% FA	0.4	32	4220	4270	4340	4440	4380
19	OPC + 30% FA	0.4	38	4270	4310	4390	4530	4470
20	OPC + 30% FA	0.4	45	4170	4190	4280	4360	4320
21	OPC + 7% SF	0.4	25	4250	4300	4410	4490	4440
22	OPC + 7% SF	0.4	32	4300	4360	4460	4560	4500
23	OPC + 7% SF	0.4	38	4270	4310	4420	4500	4440
24	OPC + 7% SF	0.4	45	4260	4300	4390	4460	4420
25	OPC + 70% GGBFS	0.4	25	3790	3810	3880	3990	3940
26	OPC + 70% GGBFS	0.4	32	3900	3940	4030	4130	4080
27	OPC + 70% GGBFS	0.4	38	3960	4000	4100	4220	4170
28	OPC + 70% GGBFS	0.4	45	3830	3860	3910	4010	3970
29	OPC + 20% NP	0.4	25	4100	4130	4210	4310	4270
30	OPC + 20% NP	0.4	32	4160	4190	4270	4350	4300
31	OPC + 20% NP	0.4	38	4230	4250	4350	4420	4380
32	OPC + 20% NP	0.4	45	4200	4220	4300	4370	4340

Table 4.13: Pulse Velocity in OPC and Blended Cement Concretes Cured by Applying a Curing Compound.

Mix No.	Cementitious Materials	w/c Ratio	Casting Temp. (°C)	Pulse Velocity (m/sec)				
				3 Days	7 Days	28 Days	90 Days	180 Days
1	100% OPC	0.3	25	4250	4280	4370	4400	4360
2	100% OPC	0.3	32	4290	4340	4420	4470	4430
3	100% OPC	0.3	38	4270	4310	4390	4430	4400
4	100% OPC	0.3	45	4260	4300	4380	4410	4380
5	100% OPC	0.4	25	4180	4200	4270	4310	4280
6	100% OPC	0.4	32	4210	4240	4310	4360	4320
7	100% OPC	0.4	38	4200	4230	4310	4340	4300
8	100% OPC	0.4	45	4190	4220	4270	4300	4280
9	100% OPC	0.45	25	4100	4120	4190	4220	4180
10	100% OPC	0.45	32	4130	4160	4230	4270	4230
11	100% OPC	0.45	38	4110	4140	4220	4250	4210
12	100% OPC	0.45	45	4110	4130	4210	4220	4180
13	OPC + 10% VFFA	0.4	25	4160	4190	4290	4350	4300
14	OPC + 10% VFFA	0.4	32	4190	4230	4320	4380	4320
15	OPC + 10% VFFA	0.4	38	4230	4270	4370	4450	4370
16	OPC + 10% VFFA	0.4	45	4220	4260	4360	4430	4370
17	OPC + 30% FA	0.4	25	4130	4150	4250	4320	4270
18	OPC + 30% FA	0.4	32	4190	4230	4290	4380	4310
19	OPC + 30% FA	0.4	38	4240	4270	4360	4460	4380
20	OPC + 30% FA	0.4	45	4150	4170	4250	4310	4260
21	OPC + 7% SF	0.4	25	4230	4270	4370	4450	4380
22	OPC + 7% SF	0.4	32	4290	4330	4420	4510	4440
23	OPC + 7% SF	0.4	38	4250	4280	4360	4430	4370
24	OPC + 7% SF	0.4	45	4240	4270	4350	4420	4360
25	OPC + 70% GGBFS	0.4	25	3780	3800	3870	3970	3910
26	OPC + 70% GGBFS	0.4	32	3880	3910	3990	4090	4020
27	OPC + 70% GGBFS	0.4	38	3950	3980	4080	4180	4120
28	OPC + 70% GGBFS	0.4	45	3810	3830	3890	3980	3930
29	OPC + 20% NP	0.4	25	4080	4120	4190	4260	4200
30	OPC + 20% NP	0.4	32	4120	4150	4230	4290	4240
31	OPC + 20% NP	0.4	38	4180	4200	4290	4360	4310
32	OPC + 20% NP	0.4	45	4170	4200	4260	4330	4280

4.4 Depth of Water Penetration

The average depth of water penetration in OPC and blended cement concrete specimens, prepared with a w/cm ratio of 0.3, 0.4 or 0.45, cast at 25, 32, 38 or 45°C and tested after 28 days of curing under moist condition, covering with wet burlap or applying a curing compound is presented in Table 4.14 along with the classification based on the criteria presented in Section 3.6.4. Moreover, quantitative analysis of the depth of water penetration of all types of concretes was carried out as shown in Table 4.15, where the depth of water penetration in each cementitious materials is expressed as a fraction of the corresponding depth in OPC concrete. As expected, the same trend was observed in mechanical tests and durability of all cementitious materials in terms of curing regime, casting temperature or w/c ratio. Additionally, a correlation between the compressive strength and depth of water penetration is developed under Section 4.7.

Table 4.14: Depth of Water Penetration and its Classification in OPC and Blended Cement Concretes at 28 Days.

Mix No.	Cementitious Materials	w/c Ratio	Casting Temp. (°C)	Water Penetration Depth[3] (mm)		
				Moist Cured	Burlap Cured	Compound Cured
1	100% OPC	0.3	25	35 (M)	45 (M)	58 (M)
2	100% OPC	0.3	32	23 (L)	34 (M)	42 (M)
3	100% OPC	0.3	38	27 (L)	42 (M)	51 (M)
4	100% OPC	0.3	45	35 (M)	46 (M)	55 (M)
5	100% OPC	0.4	25	41 (M)	51 (M)	62 (H)
6	100% OPC	0.4	32	27 (L)	40 (M)	49 (M)
7	100% OPC	0.4	38	35 (M)	47 (M)	56 (M)
8	100% OPC	0.4	45	40 (M)	53 (M)	64 (H)
9	100% OPC	0.45	25	49 (M)	61 (H)	64 (H)
10	100% OPC	0.45	32	32 (M)	48 (M)	57 (M)
11	100% OPC	0.45	38	42 (M)	54 (M)	62 (H)
12	100% OPC	0.45	45	49 (M)	64 (H)	70 (H)
13	OPC + 10% VFFA	0.4	25	36 (M)	47 (M)	60 (H)
14	OPC + 10% VFFA	0.4	32	29 (L)	37 (M)	49 (M)
15	OPC + 10% VFFA	0.4	38	24 (L)	34 (M)	44 (M)
16	OPC + 10% VFFA	0.4	45	33 (M)	40 (M)	53 (M)
17	OPC + 30% FA	0.4	25	43 (M)	53 (M)	65 (H)
18	OPC + 30% FA	0.4	32	32 (M)	42 (M)	53 (M)
19	OPC + 30% FA	0.4	38	28 (L)	40 (M)	50 (M)
20	OPC + 30% FA	0.4	45	44 (M)	58 (M)	69 (H)
21	OPC + 7% SF	0.4	25	34 (M)	45 (M)	57 (M)
22	OPC + 7% SF	0.4	32	23 (L)	32 (M)	45 (M)
23	OPC + 7% SF	0.4	38	26 (L)	36 (M)	47 (M)
24	OPC + 7% SF	0.4	45	35 (M)	45 (M)	55 (M)
25	OPC + 70% GGBFS	0.4	25	49 (M)	61 (H)	70 (H)
26	OPC + 70% GGBFS	0.4	32	46 (M)	57 (M)	65 (H)
27	OPC + 70% GGBFS	0.4	38	37 (M)	50 (M)	58 (M)
28	OPC + 70% GGBFS	0.4	45	43 (M)	56 (M)	67 (H)
29	OPC + 20% NP	0.4	25	46 (M)	56 (M)	68 (H)
30	OPC + 20% NP	0.4	32	35 (M)	48 (M)	58 (M)
31	OPC + 20% NP	0.4	38	33 (M)	45 (M)	53 (M)
32	OPC + 20% NP	0.4	45	39 (M)	53 (M)	66 (H)

[3] H, M and L represents High, Medium and Low permeability of water, respectively.

Table 4.15: Depth of Water Penetration in Blended Cement Concretes Compared to the Depth in OPC Concrete (0.4 w/c) - Average of all Curing Regimes.

Mix No.	Cementitious Materials	w/c Ratio	Casting Temp. (°C)	DP (Blended Cement) / DP (OPC) [4]			
				Moist Cured	Burlap Cured	Comp-ound Cured	Average
13	OPC + 10% VFFA	0.4	25	0.88	0.92	0.97	0.92
14	OPC + 10% VFFA	0.4	32	1.07	0.93	1.00	1.00
15	OPC + 10% VFFA	0.4	38	0.69	0.72	0.79	0.73
16	OPC + 10% VFFA	0.4	45	0.83	0.75	0.83	0.80
Range							**0.73-1.00**
17	OPC + 30% FA	0.4	25	1.05	1.04	1.05	1.05
18	OPC + 30% FA	0.4	32	1.19	1.05	1.08	1.11
19	OPC + 30% FA	0.4	38	0.80	0.85	0.89	0.85
20	OPC + 30% FA	0.4	45	1.10	1.09	1.08	1.09
Range							**0.85-1.11**
21	OPC + 7% SF	0.4	25	0.83	0.88	0.92	0.88
22	OPC + 7% SF	0.4	32	0.85	0.80	0.92	0.86
23	OPC + 7% SF	0.4	38	0.74	0.77	0.84	0.78
24	OPC + 7% SF	0.4	45	0.88	0.85	0.86	0.86
Range							**0.78-0.88**
25	OPC + 70% GGBFS	0.4	25	1.20	1.20	1.13	1.17
26	OPC + 70% GGBFS	0.4	32	1.70	1.43	1.33	1.49
27	OPC + 70% GGBFS	0.4	38	1.06	1.06	1.04	1.05
28	OPC + 70% GGBFS	0.4	45	1.08	1.06	1.05	1.06
Range							**1.05-1.49**
29	OPC + 20% NP	0.4	25	1.12	1.10	1.10	1.11
30	OPC + 20% NP	0.4	32	1.30	1.20	1.18	1.23
31	OPC + 20% NP	0.4	38	0.94	0.96	0.95	0.95
32	OPC + 20% NP	0.4	45	0.98	1.00	1.03	1.00
Range							**0.95-1.23**

[4] Ratio of depth of water penetration in blended cement concretes to plain cement concretes.

4.4.1 OPC Concrete

The depth of water penetration in OPC concrete (100% OPC) specimens prepared with w/c ratio of 0.3, 0.4 or 0.45, cast at 25, 32, 38 or 45°C and cured by water ponding, covering with wet burlap or applying a curing compound is depicted in Figures 4.55 through 4.57, respectively.

Effect of Curing Regime on Depth of Water Penetration in OPC Concrete

The depth of water penetration in the moist cured concrete specimens was less than that in the concrete specimens cured by covering with wet burlap or applying a curing compound. As shown in Table 4.14, irrespective of any casting temperature and w/c ratio studied, the depth of water penetration after 28 days of moist curing was on average 26.0 and 37.0% less than that in the concrete specimens cured by covering with wet burlap or applying a curing compound, respectively. Further, the depth of water penetration in the concrete specimen cured by covering with wet burlap was less than that in the concrete specimens cured by application of a curing compound by about 14.8% on average. The difference in the depth of water penetration by different curing technique is ascribed to the water retention that preserves internal moisture for maintaining a favorable humid condition for hydration reaction thereby producing a dense concrete. Saricimen et al. [87] measured volume of voids and absorption test on plain and pozzolanic concretes and concluded that to produce the least permeable concrete, continuous water curing (at laboratory) is better than outdoor curing.

Effect of Casting Temperature on Depth of Water Penetration in OPC Concrete

Regardless of w/c ratios and curing regimes utilized, the minimum depth of water penetration was noted in the concrete specimens cast at 32°C followed by those that were cast at 38°C while the difference between depth of water penetration in the concrete specimens cast at 25 or 45°C was marginal but significantly higher than those cast at other temperatures, as shown in Table 4.14 and depicted in Figures 4.55 through 4.57. On average, the 28-day depth of water penetration in the concrete specimens cast at 32°C was 24.5, 15.4 and 26.1% less than that in the concrete specimens cast at 25, 38 or 45°C, respectively.

Effect of w/c Ratio on Depth of Water Penetration in OPC Concrete

As expected, the depth of water penetration in the OPC concrete mixes increased with the increase in the w/c ratio. For all casting temperatures and curing regimes, the 28-day depth of water penetration in the concrete specimens prepared with w/c ratio of 0.3 was on average 12.8 and 24.1% less than that in the concrete specimens prepared with w/c ratio of 0.4 or 0.45, respectively. Further, the depth of water penetration in the concrete specimen prepared with w/c ratio of 0.4 was on average 13.0% less than that in the concrete specimens prepared with w/c ratio of 0.45. The higher depth of water penetration with an increase in the w/c ratio is probably due to the porous pore structure caused by increase in the w/c ratio. Al-Amoudi [19] observed that the concrete permeability is significantly reduced for a w/c ratio below 0.45. He suggested that to obtain good durability, w/c ratio should be less than 0.45, and preferably around 0.40. The coefficient of permeability increases considerably with the increase in the w/c ratios: it increases by 4 times over the range of w/c ratio of 0.26 to 0.75 and by 2 orders of magnitude over the range of 0.45 to 0.75 [116]. The permeability of concrete increases significantly at w/c ratio more than 0.4 as the capillaries become segmented at this limit of w/c ratio and, hence, increases the ingress of aggressive species into concrete [32].

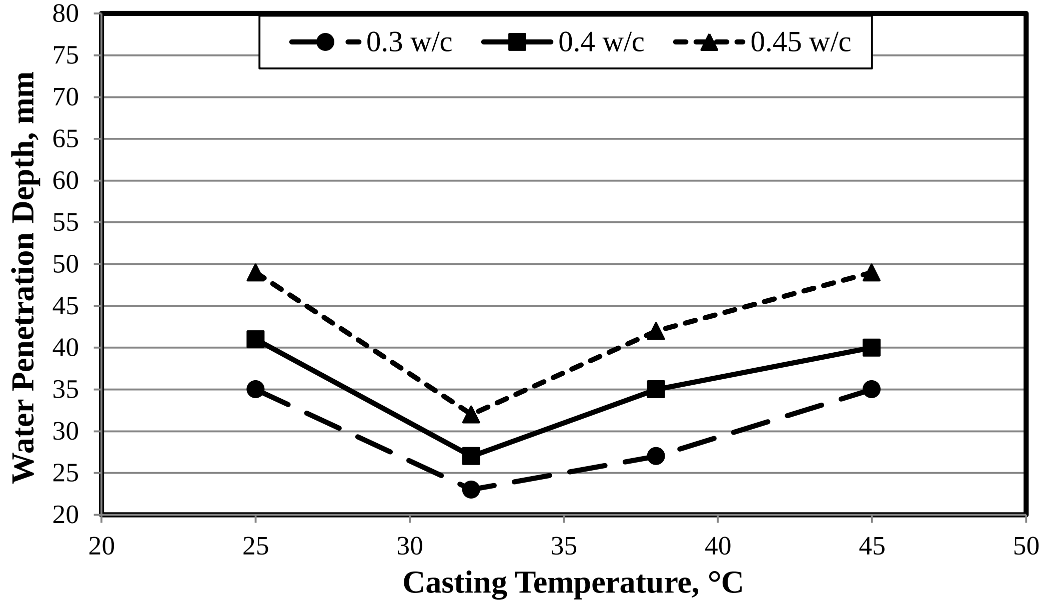

Figure 4.55: Depth of Water Penetration in OPC Concretes Prepared with w/c Ratio of 0.3-0.45 and Cast at 25-45°C after 28 Days of Moist Curing.

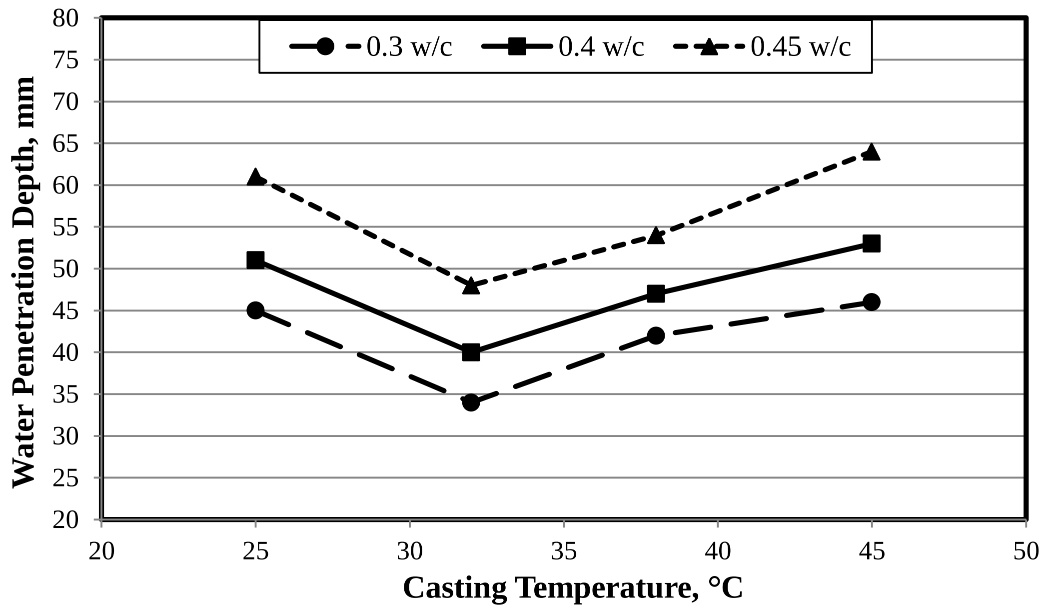

Figure 4.56: Depth of Water Penetration in OPC Concretes Prepared with w/c Ratio of 0.3-0.45 and Cast at 25-45°C after 28 Days of Curing by Covering with Wet Burlap.

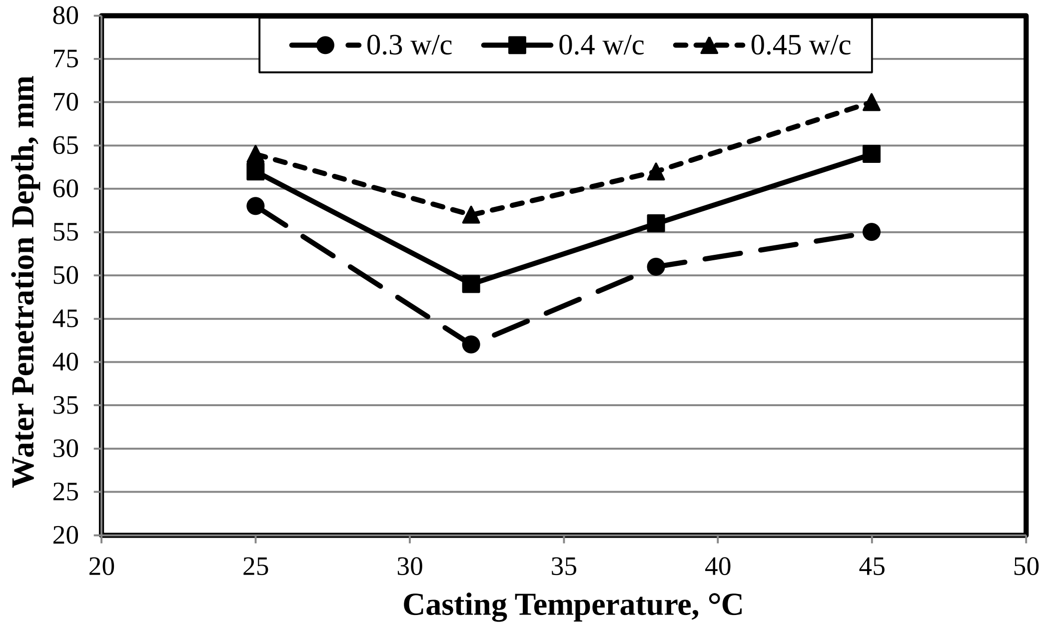

Figure 4.57: Depth of Water Penetration in OPC Concretes Prepared with w/c Ratio of 0.3-0.45 and Cast at 25-45°C after 28 Days of Applying a Curing Compound.

4.4.2 VFFA Cement Concrete

The effect of partial replacement of OPC by 10% VFFA cement on the depth of water penetration is discussed in this section. For each curing regime, the depth of water penetration versus casting temperature curves were plotted for all the concrete specimens prepared at a constant w/cm ratio of 0.4 and cast at varying temperatures of 25 to 45°C, as shown in Figure 4.58.

Effect of Curing Regime on Depth of Water Penetration in VFFA Cement Concrete

The depth of water penetration in the moist cured concrete specimens was less than that in the concrete specimens cured by covering with wet burlap or applying a curing compound. On average from Table 4.14, the 28-day depth of water penetration in the moist cured concrete specimens was 22.8 and 40.8% less than that in the concrete specimens cured by covering with wet burlap or applying a curing compound, respectively. Further, the depth of water penetration in the concrete specimens cured by covering with wet burlap was 23.3% less than that in the concrete specimens cured by applying a curing compound. This difference in the depth of water penetration due to varying the curing regime is ascribed to the water retention that preserves internal moisture for maintaining a favorable humid condition for hydration and pozzolanic reactions.

Effect of Casting Temperature on Depth of Water Penetration in VFFA Cement Concrete

Irrespective of the curing regime investigated, the minimum depth of water penetration was measured in the concrete specimens cast at 38°C followed by those that were cast at 32°C while the depth of water penetration in the concrete specimens cast at 25 and 45°C was relatively high, as shown in Table 4.14 and depicted in Figure 4.58. On average, the 28-day depth of water penetration in the concrete specimens cast at 38°C was 28.7, 11.3 and 19.1% less than that in the concrete specimens cast at 25, 32 or 45°C, respectively.

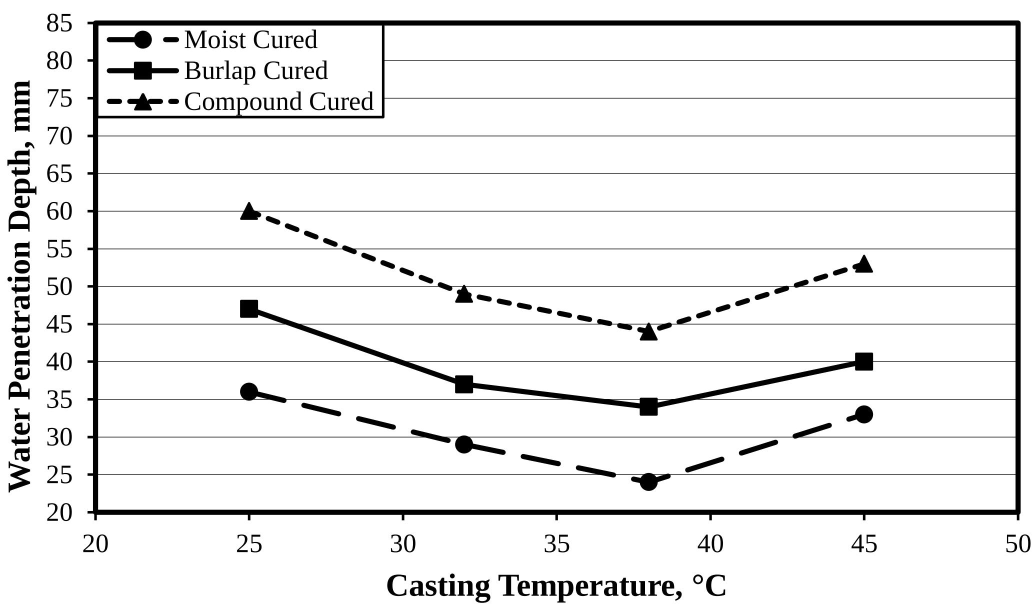

Figure 4.58: Depth of Water Penetration in VFFA Cement Concretes at 28 Days.

4.4.3 FA Cement Concrete

The depth of water penetration in FA cement concrete (OPC + 30% FA) specimens prepared with a w/cm ratio of 0.4, cast at 25, 32, 38 or 45°C and cured under moist condition, covering with wet burlap or applying a curing compound is depicted in Figure 4.59.

Effect of Curing Regime on Depth of Water Penetration in FA Cement Concrete

The 28-day depth of water penetration in the moist cured concrete specimens was on average 23.8 and 38.0% less than that in the concrete specimens cured by covering with wet burlap or applying a curing compound, respectively, as shown in Table 4.14. Further, the depth of water penetration in the concrete specimens cured by covering with wet burlap was less than that in the concrete specimens cured by applying a curing compound. This difference was about 18.6% on average.

Effect of Casting Temperature on Depth of Water Penetration in FA Cement Concrete

For all curing regimes, 38°C was the optimum temperature at which the minimum depth of water penetration was measured in the concrete specimens followed by those that were cast at 32°C, while the difference between the depth of water penetration in the concrete specimens cast at 25 or 45°C was marginal but higher than those cast at other temperatures, as shown in Table 4.14 and depicted in Figure 4.59. On average, the 28-day depth of water penetration in the concrete specimens cast at 38°C was 26.7, 7.1 and 31.0% less than that in the concrete specimens cast at 25, 32 or 45°C, respectively.

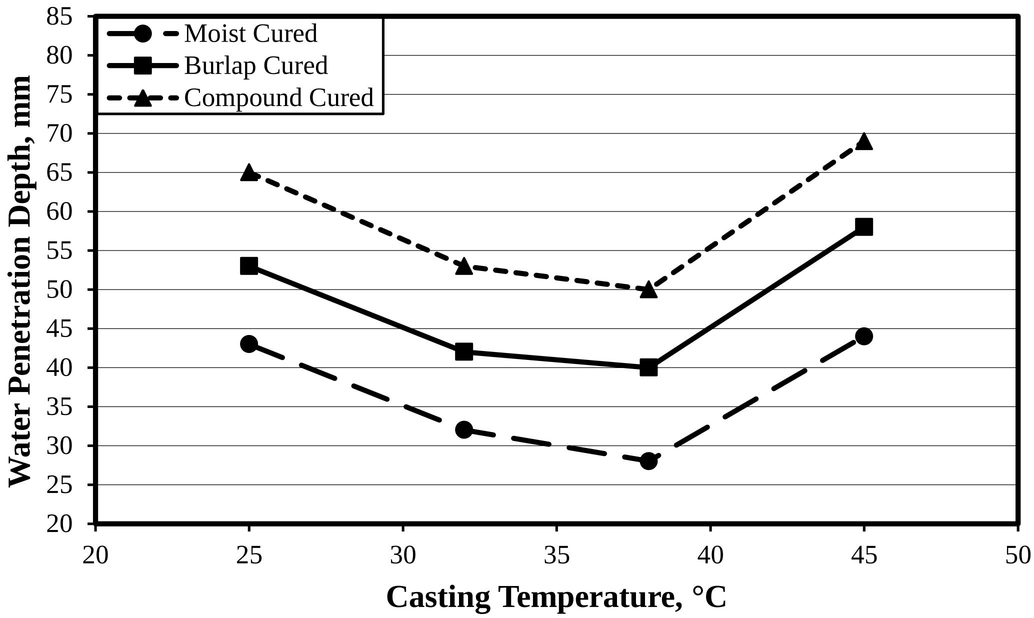

Figure 4.59: Depth of Water Penetration in FA Cement Concretes at 28 Days.

4.4.4 SF Cement Concrete

The influence of partial replacement of OPC by 7% SF cement on the depth of water penetration is discussed in this section. For each curing regime, the depth of water penetration versus casting temperature curves were plotted for all the concrete specimens prepared at a constant w/cm ratio of 0.4 and cast at range of temperatures of 25-45°C, as shown in Figure 4.60.

Effect of Curing Regime on Depth of Water Penetration in SF Cement Concrete

The minimum depth of water penetration was measured in all concrete specimens cured under moist condition followed by those specimens that were cured by covering with wet burlap or applying a curing compound, in increasing order. On average, the 28-day depth of water penetration in the moist cured concrete specimens was 25.3 and 42.2% less than that in the concrete specimens cured by covering with wet burlap or applying a curing compound, respectively, as shown in Table 4.14. Further, the depth of water penetration in the concrete specimens cured by covering with wet burlap was 22.6% less than that in the concrete specimens cured by applying a curing compound.

Effect of Casting Temperature on Depth of Water Penetration in SF Cement Concrete

The minimum depth of water penetration was measured in the concrete specimens cast at 32°C (alike 100% OPC concrete specimens) followed by those that were cast at 38°C, while the depth of water penetration in the concrete specimens cast at 25 or 45°C was approximately the same but higher than those cast at other temperatures, as shown in Table 4.14 and depicted in Figure 4.60. On average, the 28-day depth of water penetration in the concrete specimens cast at 32°C was 26.5, 8.3 and 25.9% less than that in the concrete specimens cast at 25, 38 or 45°C, respectively.

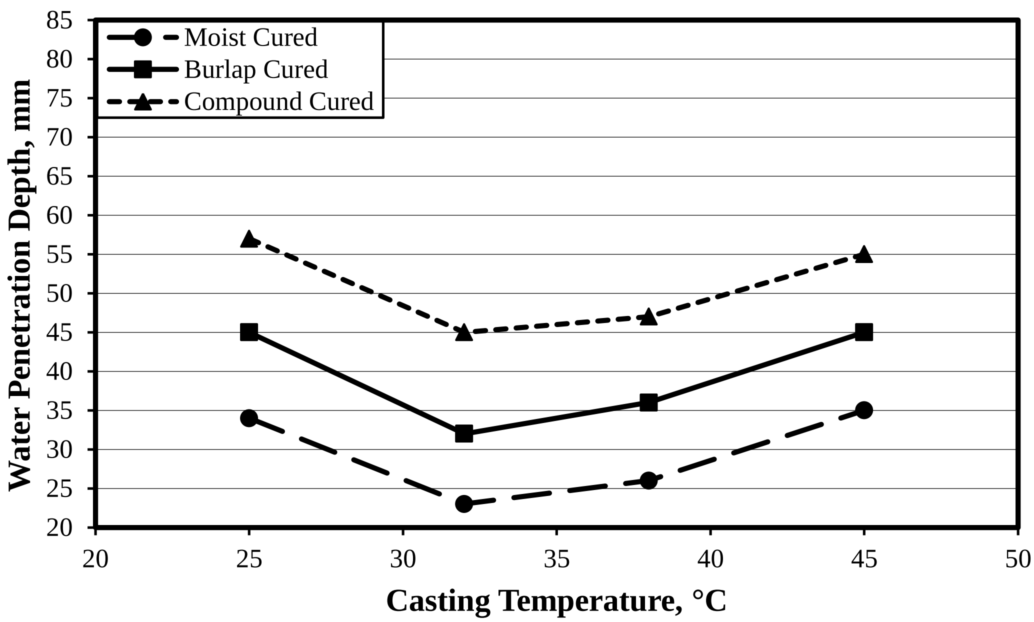

Figure 4.60: Depth of Water Penetration in SF Cement Concretes at 28 Days.

4.4.5 GGBFS Cement Concrete

The depth of water penetration in GGBFS cement concrete (OPC + 70% GGBFS) specimens prepared with a w/cm ratio of 0.4, cast at 25, 32, 38 or 45°C and cured under moist condition, covering with wet burlap or applying a curing compound is depicted in Figure 4.61.

Effect of Curing Regime on Depth of Water Penetration in GGBFS Cement Concrete

From Table 4.14, the 28-day depth of water penetration in the moist cured concrete specimens was on average 21.9 and 32.7% less than that in the concrete specimens cured by covering with wet burlap or applying a curing compound, respectively. Further, the depth of water penetration in the concrete specimens cured by covering with wet burlap was 13.8% less than that in the concrete specimens cured by applying a curing compound.

Effect of Casting Temperature on Depth of Water Penetration in GGBFS Cement Concrete

Regardless of the curing regime, 38°C was the optimum temperature at which the minimum depth of water penetration was recorded in the concrete specimens followed by those that were cast at 32 or 45°C, while the depth of water penetration in the concrete specimens cast at 25°C was the highest, as shown in Table 4.14 and depicted in Figure 4.61. On average, the 28-day depth of water penetration in the concrete specimens cast at 38°C was 19.5, 13.7 and 12.7% less than that in the concrete specimens cast at 25, 32 or 45°C, respectively. Gowripalan et al. [117] examined the effect of curing temperature on the durability of 70% GGBFS cement concrete and reported that porosity is lower when cured at 35°C than at 21°C.

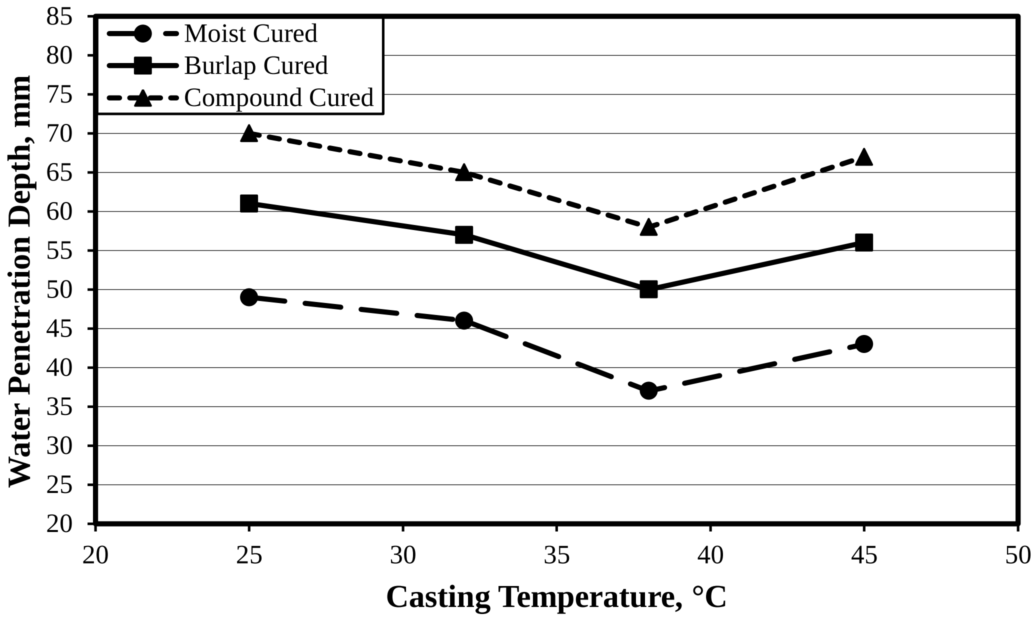

Figure 4.61: Depth of Water Penetration in GGBFS Cement Concretes at 28 Days.

4.4.6 NP Cement Concrete

The depth of water penetration in NP cement concrete specimens prepared with a constant w/cm ratio of 0.4, cast at varying temperatures of 25, 32, 38 or 45°C and cured by water ponding, covering with wet burlap or application of a curing compound is depicted in Figure 4.62.

Effect of Curing Regime on Depth of Water Penetration in NP Cement Concrete

On average, the 28-day depth of water penetration in the moist cured concrete specimens was 24.3 and 37.6% less than that in the concrete specimens cured by covering with wet burlap or applying a curing compound, respectively, as shown in Table 4.14. Further, the depth of water penetration in the concrete specimens cured by covering with wet burlap was 17.6% less than that in the concrete specimens cured by applying a curing compound.

Effect of Casting Temperature on Depth of Water Penetration in NP Cement Concrete

For all the curing technique utilized, the minimum depth of water penetration was observed in the concrete specimens cast at 38°C followed by those that were cast at 32°C, while the depth of water penetration in the concrete specimens cast at 25 or 45°C was relatively high, as shown in Table 4.14 and depicted in Figure 4.62. On average, the 28-day depth of water penetration in the concrete specimens cast at 38°C was 22.9, 7.1 and 17.1% less than that in the concrete specimens cast at 25, 32 or 45°C, respectively.

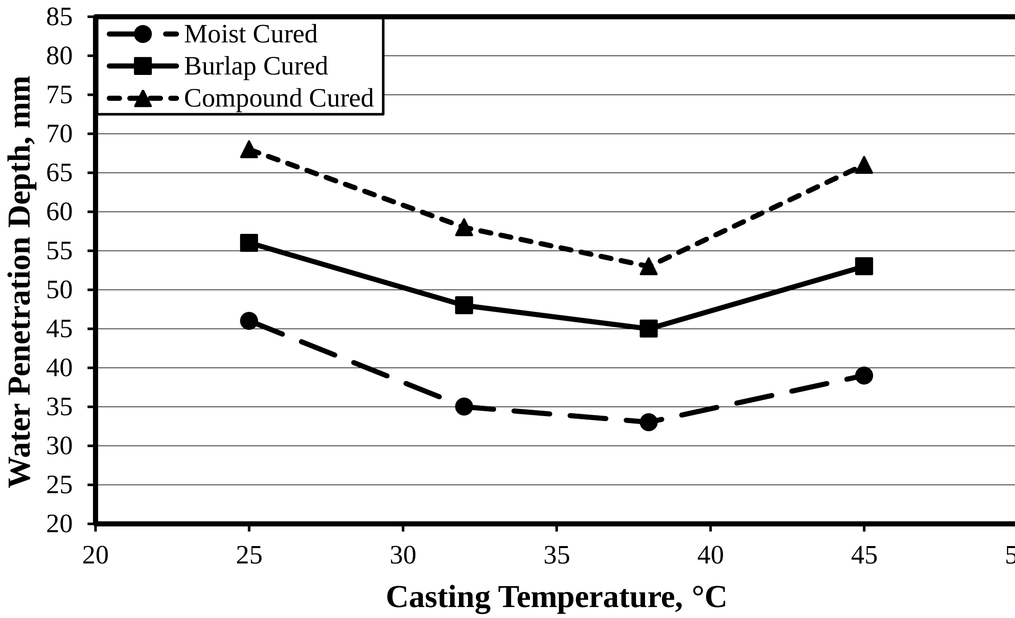

Figure 4.62: Depth of Water Penetration in NP Cement Concretes at 28 Days.

4.4.7 Comparison of Depth of Water Penetration in Cementitious Materials

Figures 4.63 through 4.65 depict the 28-day depth of water penetration in the plain and blended cement concrete specimens prepared with a constant w/cm ratio of 0.4, cast at 25 to 45°C and cured under moist condition, covering with wet burlap or applying a curing compound, respectively. As explained earlier, irrespective of the curing regime studied, the depth of water penetration decreased up to 32°C. However, a further rise in the casting temperature increased the depth of water penetration. An exception to this trend was noted in FA, VFFA, NP and GGBFS cement concretes. In these concrete specimens, the depth of water penetration continued to decrease up to a temperature of 38°C; thereafter, there was an increase in the depth of water penetration.

It was also noted that regardless of any curing condition and casting temperature utilized, at 25 and 32°C, the minimum depth of water penetration was attained in the SF cement concrete specimens while the maximum depth of water penetration was noted in the GGBFS cement concrete specimens. However, at 38 and 45°C, the minimum depth of water penetration was recorded in VFFA cement concretes. The maximum depth of water penetration at these temperatures was measured in GGBFS and in both GGBFS and FA cement concretes, respectively. The initial decrease in the depth of water penetration may be attributed to the increase in the hydration reaction while the increase in depth of water penetration, with increasing temperature, may be the consequence of formation of micro cracks.

The data in Table 4.15 shows the ratio of 28-day depth of water penetration in blended cement concretes to OPC concretes for a range of casting temperatures and average of curing regimes. The ratio of VFFA to OPC concretes was in the range of 0.73-1.00 (indicating that the depth of water penetration in VFFA cement concrete was about 27% lower than OPC concrete at the casting temperature of 38°C while it was equivalent to OPC concretes at 32°C). The range of ratio of FA, SF GGBFS and NP to OPC concrete was 0.85-1.11, 0.78-0.88, 1.05-1.49, and 0.95-1.23, respectively. The lowest and highest ratio of depth of penetration was noticed in VFFA and GGBFS cement concretes, respectively. Al-Amoudi et at. [91] also reported almost the same ratio of depth of water penetration of SF to OPC and FA to OPC i.e. 0.74 and 0.93, respectively. It was concluded from the test results in studies [44,45] that incorporating SF, FA and GGBFS into plain cement concrete can greatly improve the durability of concrete. Additionally, it was revealed that from the industrial by-products examined, silica fume performed better than others. In a study [118] it was observed that when the blending materials utilized are finer than ordinary Portland cement, particle packing is improved and permeability is reduced provided that adequate curing is done. The increased penetrability of chlorides was observed when neat OPC concrete is cured at 50°C [119], which was ascribed to the development of micro cracks. The higher initial permeability of FA cement is due to its slow reaction in the concrete. However, the permeability of FA concrete is very low at later ages [33]. The influence of reduced permeability of SF cement concrete compared to the hydrated cement concrete is even more than that of compressive strength. A 5% SF content concrete is reported to have a lower coefficient of permeability by 3 times of magnitude as compared to OPC concrete because SF reduces both the permeability of transition zone in the vicinity of aggregates and permeability of the overall cement paste [120]. Rasheeduzafar [121] found that due to pore refinement resulting from the pozzolanic reactions, the coefficient of permeability in 20% SF and 30% FA cement concretes is reduced to about 16 and 5 times, respectively at 180 day. The lower water penetration depth in GGBFS and OPC concrete compared to SF, VFFA and FA concrete were also reported by Elsayed [93].

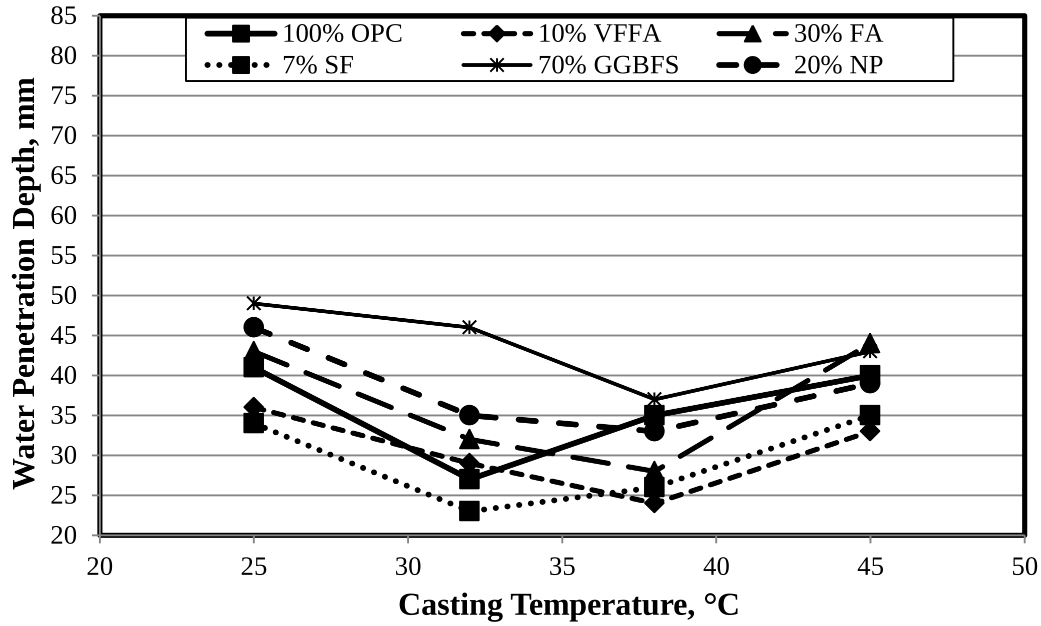

Figure 4.63: Depth of Water Penetration in OPC and Blended Cement Concretes Prepared with w/cm Ratio of 0.4 and Cast at 25-45°C after 28 Days of Moist Curing.

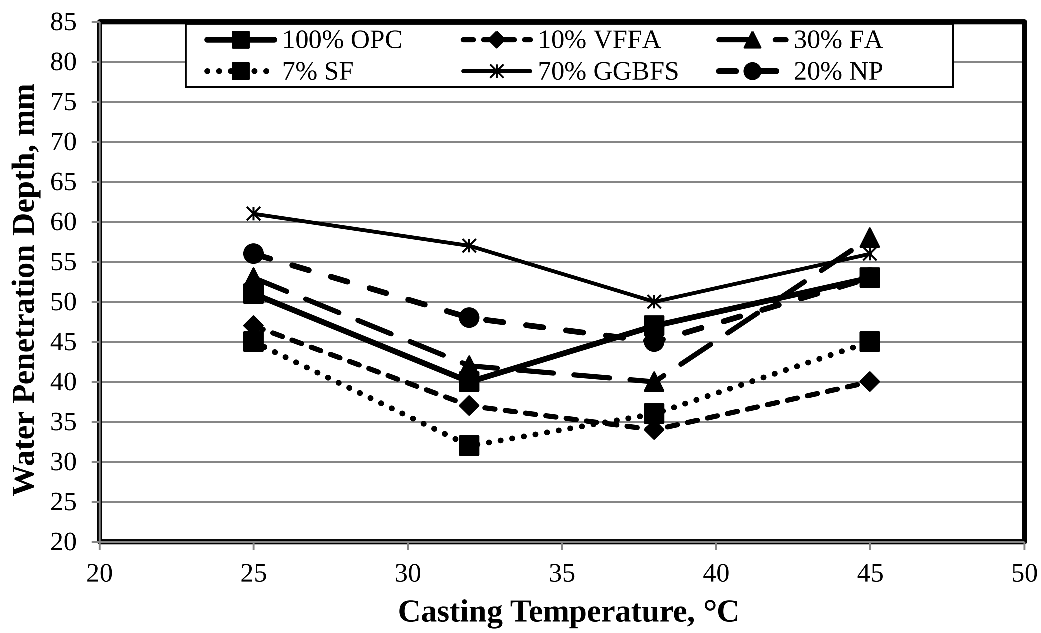

Figure 4.64: Depth of Water Penetration in OPC and Blended Cement Concretes Prepared with w/cm Ratio of 0.4 and Cast at 25-45°C after 28 Days of Curing by Covering with Wet Burlap.

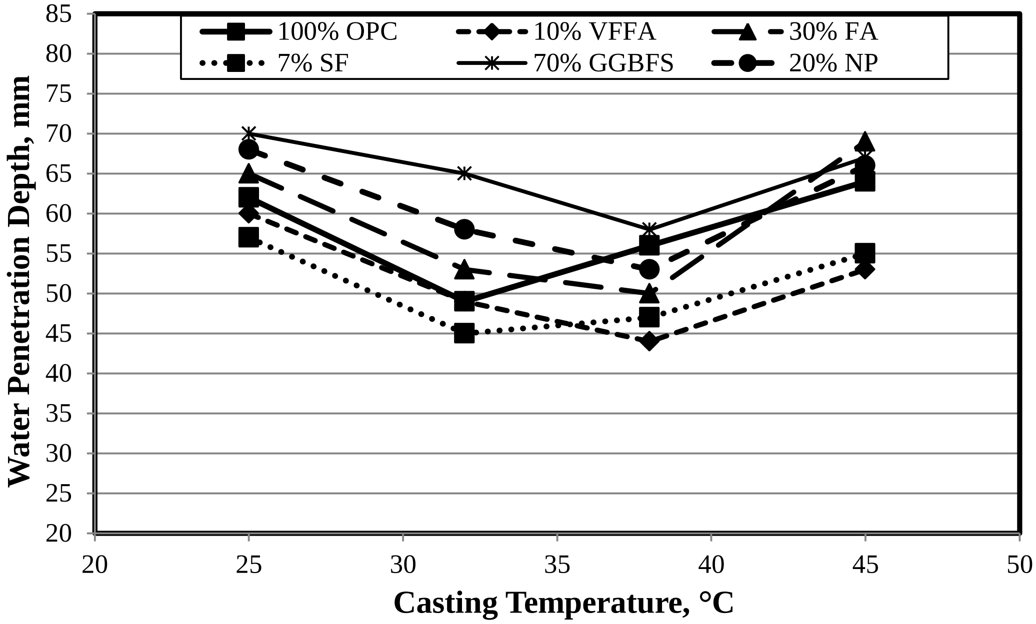

Figure 4.65: Depth of Water Penetration in OPC and Blended Cement Concretes Prepared with w/cm Ratio of 0.4 and Cast at 25-45°C after 28 Days of Applying a Curing Compound.

4.5 Plastic Shrinkage Strain

The average plastic shrinkage strain in OPC and blended cement concrete specimens, prepared with a w/cm ratio of 0.3, 0.4 or 0.45, cast at 25, 32, 38 or 45°C and cured by applying a curing compound or covering with a plastic sheet was recorded and these values for typical OPC concretes prepared with a w/c ratio of 0.4 is summarized in Table 4.16. However, the maximum plastic shrinkage strain recorded in each specimen is summarized in Table 4.17. Further, quantitative analysis of the plastic shrinkage strain of all types of concretes was carried out as shown in Table 4.18, where the plastic shrinkage strain in each cementitious materials is expressed as a fraction of the corresponding shrinkage strain in OPC concrete.

Table 4.16: Typical Plastic Shrinkage Strain in OPC Concretes Prepared with w/c Ratio of 0.4.

Time (min)	Plastic Shrinkage Strain (microns)							
	25°C		32°C		38°C		45°C	
	Curing Comp-ound	Plastic Sheet	Curing Comp-ound	Plastic Sheet	Curing Comp-ound	Plastic Sheet	Curing Comp-ound	Plastic Sheet
0	0	0	0	0	0	0	0	0
10	25	1	60	19	196	65	51	73
20	51	39	67	64	224	103	81	110
30	75	78	80	121	229	101	119	147
40	97	112	85	183	240	142	161	173
50	121	141	95	232	244	210	154	208
60	143	163	111	278	251	248	210	239
70	167	184	126	313	268	282	251	271
80	177	229	134	339	288	305	289	303
90	202	273	147	379	296	326	302	340
100	215	341	156	422	314	352	327	356
110	243	421	170	446	326	384	349	391
120	296	507	196	478	365	408	371	421
130	407	581	240	506	394	442	386	442
140	567	627	269	545	405	464	398	456
150	698	662	297	606	418	491	414	477
160	756	682	310	652	436	520	404	509
170	806	697	310	673	455	551	415	532
180	856	710	327	688	470	584	411	572
190	861	720	338	708	483	606	401	617
200	861	755	361	726	494	639	398	658
210	887	780	353	738	504	663	393	682
220	888	808	400	750	516	684	397	706
230	891	819	409	772	525	710	416	714
240	889	840	418	796	541	731	443	740
250	903	865	427	808	549	755	466	769
260	901	883	440	811	560	807	486	785
270	897	900	447	829	577	828	507	799
280	909	914	457	826	592	844	509	797
290	912	931	478	825	602	859	542	819
300	935	947	488	829	654	872	584	854
310	942	959	499	832	660	892	598	889
320	956	968	511	839	663	905	612	952
330	974	987	521	848	670	923	625	972
340	977	1010	531	856	679	934	640	982

350	996	1028	539	863	688	949	672	989
360	998	1048	544	873	695	961	686	994
390	988	1073	554	879	698	960	689	994
420	1009	1102	561	886	703	970	727	1009
450	1009	1133	569	897	714	975	761	1024
480	1055	1162	577	903	715	986	778	1032
510	1064	1192	587	911	716	988	808	1048
540	1062	1216	596	921	714	985	823	1066
570	1073	1243	595	929	712	989	845	1094
600	1074	1265	594	932	713	990	874	1109
630	1068	1287	591	931	720	992	906	1125
660	1058	1302	585	933	715	996	921	1139
690	1049	1353	580	936	714	1000	947	1156
720	1044	1368	575	940	715	997	952	1176
750	1038	1373	564	936	720	996	955	1187
780	1031	1372	558	928	722	996	957	1198
810	1029	1372	554	927	718	998	957	1198
840	1028	1373	558	929	715	1001	956	1199

Table 4.17: Maximum Plastic Shrinkage Strain in OPC and Blended Cement Concretes.

Mix No.	Cementitious Materials	w/c Ratio	Casting Temp. (°C)	Maximum Plastic Shrinkage Strain (microns)	
				Curing Compound	Plastic Sheet
1	100% OPC	0.3	25	719	1137
2	100% OPC	0.3	32	315	663
3	100% OPC	0.3	38	605	916
4	100% OPC	0.3	45	837	1135
5	100% OPC	0.4	25	1074	1373
6	100% OPC	0.4	32	596	940
7	100% OPC	0.4	38	722	1001
8	100% OPC	0.4	45	957	1199
9	100% OPC	0.45	25	1268	1593
10	100% OPC	0.45	32	775	1066
11	100% OPC	0.45	38	1079	1396
12	100% OPC	0.45	45	1205	1438
13	OPC + 10% VFFA	0.4	25	1441	1611
14	OPC + 10% VFFA	0.4	32	907	1024
15	OPC + 10% VFFA	0.4	38	666	807
16	OPC + 10% VFFA	0.4	45	1078	1244
17	OPC + 30% FA	0.4	25	1263	1520
18	OPC + 30% FA	0.4	32	1082	1392
19	OPC + 30% FA	0.4	38	538	949
20	OPC + 30% FA	0.4	45	721	1091
21	OPC + 7% SF	0.4	25	1198	1370
22	OPC + 7% SF	0.4	32	1083	1362
23	OPC + 7% SF	0.4	38	718	937
24	OPC + 7% SF	0.4	45	902	1084
25	OPC + 70% GGBFS	0.4	25	1320	1560
26	OPC + 70% GGBFS	0.4	32	963	1257
27	OPC + 70% GGBFS	0.4	38	784	1041
28	OPC + 70% GGBFS	0.4	45	778	959
29	OPC + 20% NP	0.4	25	1084	1253
30	OPC + 20% NP	0.4	32	902	1064
31	OPC + 20% NP	0.4	38	607	778
32	OPC + 20% NP	0.4	45	896	1019

Table 4.18: Plastic Shrinkage Strain in Blended Cement Concretes Compared to the Strain in OPC Concrete (0.4 w/c) - Average of all Curing Regimes.

Mix No.	Cementitious Materials	w/c Ratio	Casting Temp. (°C)	PS (Blended Cement) / PS (OPC) [5]		
				Curing Compound	Plastic Sheet	Average
13	OPC + 10% VFFA	0.4	25	1.34	1.17	1.26
14	OPC + 10% VFFA	0.4	32	1.52	1.09	1.31
15	OPC + 10% VFFA	0.4	38	0.92	0.81	0.86
16	OPC + 10% VFFA	0.4	45	1.13	1.04	1.08
Range						**0.86 - 1.31**
17	OPC + 30% FA	0.4	25	1.18	1.11	1.14
18	OPC + 30% FA	0.4	32	1.82	1.48	1.65
19	OPC + 30% FA	0.4	38	0.75	0.95	0.85
20	OPC + 30% FA	0.4	45	0.75	0.91	0.83
Range						**0.83 - 1.65**
21	OPC + 7% SF	0.4	25	1.12	1.00	1.06
22	OPC + 7% SF	0.4	32	1.82	1.45	1.63
23	OPC + 7% SF	0.4	38	0.99	0.94	0.97
24	OPC + 7% SF	0.4	45	0.94	0.90	0.92
Range						**0.92 - 1.63**
25	OPC + 70% GGBFS	0.4	25	1.23	1.14	1.18
26	OPC + 70% GGBFS	0.4	32	1.62	1.34	1.48
27	OPC + 70% GGBFS	0.4	38	1.09	1.04	1.06
28	OPC + 70% GGBFS	0.4	45	0.81	0.80	0.81
Range						**0.81 - 1.48**
29	OPC + 20% NP	0.4	25	1.01	0.91	0.96
30	OPC + 20% NP	0.4	32	1.51	1.13	1.32
31	OPC + 20% NP	0.4	38	0.84	0.78	0.81
32	OPC + 20% NP	0.4	45	0.94	0.85	0.89
Range						**0.81 - 1.32**

[5] Ratio of plastic shrinkage strain in blended cement concretes to plain cement concretes.

4.5.1 OPC Concrete

The variation of plastic shrinkage strain with time in OPC concrete (100% OPC) specimens prepared with w/c ratio of 0.3, 0.4 or 0.45, cast at 25, 32, 38 or 45°C and cured by application of a curing compound or covering with a plastic sheet is depicted in Figures 4.66 through 4.77.

Effect of Curing Regime on Plastic Shrinkage Strain in OPC Concrete

The plastic shrinkage strain in the concrete specimens cured by applying a curing compound was less than that in the concrete specimens cured in air by covering with a plastic sheet. Irrespective of casting temperatures and w/c ratios, the maximum plastic shrinkage strain in the concrete specimens cured by applying a curing compound was on average 26.7% less than that in the concrete specimens cured in air, as shown in Table 4.17. The lower plastic shrinkage strain in the concrete specimens cured by applying a curing compound is attributed to the lower loss of water due to a formation of an impermeable layer over the concrete surface. Other studies also reported superior performance due to the application of the curing compounds as compared to curing in air or covering with plastic sheet in decreasing the plastic shrinkage strain in both OPC and blended cement concretes (7% SF, 10% VFFA and 30% FA), under hot weather conditions [7,79]. Al-Gahtani [7] found out that the difference between plastic shrinkage strain in OPC concrete specimens cured in air or applying a water-based curing membrane was about 24.0%.

Effect of Casting Temperature on Plastic Shrinkage Strain in OPC Concrete

It was also noted that regardless of the w/c ratio and curing regime utilized, the least value of maximum plastic shrinkage strain was recorded in the mixes that were cast at

32°C followed by those that were cast at 38°C, while the highest shrinkage strain was observed in mixes cast at 25°C, as shown in Table 4.17 and depicted in Figures 4.78 and 4.79. On average, the maximum plastic shrinkage strain in the concrete specimens cast at 32°C was 39.3, 23.9 and 35.7% less than that in the concrete specimens cast at 25, 38 or 45°C, respectively. The highest plastic shrinkage strain at the casting temperature of 25°C may be attributed to the greater temperature difference between the concrete temperature and the ambient summer temperature. Alhozaimy and Negheimish [122] determined plastic shrinkage in hot weather where the outdoor ambient temperature was 38 to 42°C and the concrete was cast at 25, 32 and 38°C. They concluded that plastic shrinkage cracking tends to decrease with increasing concrete temperature and the minimum cracking at higher casting temperature is related to the decreased setting time. Senbetta and Bury [123] measured the plastic shrinkage cracking in cold weather where the ambient temperature was about 0°C and mortar specimens were cast at 4 or 18°C. The authors reported that the greater the difference between the ambient temperature and concrete temperature was, the higher would be the rate of evaporation and shrinkage cracking. FitzGibbon [124] suggested that when there is temperature difference of about 20°C between the interior and external part of concrete, cracking in the interior may occur. Further, according to ACI Code 305 [10], plastic shrinkage cracking is likely to occur when the rate of evaporation of mix water exceeds the rate of bleeding and the critical limit for the rate of evaporation is 1.0 kg/m^2-h. On contrary, Almusallam et al. [73] indicated that plastic shrinkage cracking appeared when the evaporation rate was in the range of 0.2 to 0.7 kg/m^2-h, under hot environmental conditions.

Effect of w/c Ratio on Plastic Shrinkage Strain in OPC Concrete

As expected, the plastic shrinkage strain in OPC concrete specimens, with similar casting temperature and curing method, increased with the increase in the w/c ratio. On average, the maximum plastic shrinkage strain in the concrete specimens prepared with w/c ratio of 0.3 was 19.6 and 35.6% less than that in the concrete specimens prepared with w/c ratio of 0.4 or 0.45, respectively, as shown in Table 4.17. Further, the plastic shrinkage strain in the concrete specimens prepared with w/c ratio of 0.4 was on average 20.0% less than that in the concrete specimens prepared with w/c ratio of 0.45. The increased plastic shrinkage strain with an increase in the w/c ratio may be attributed to the excessive water available for evaporation.

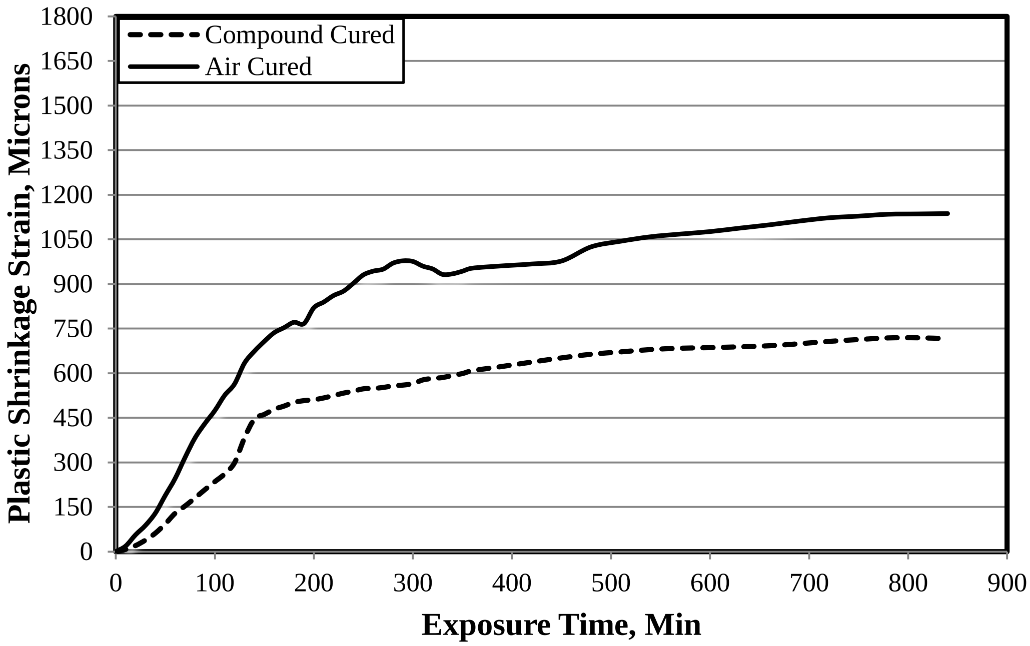

Figure 4.66: Plastic Shrinkage Strain in OPC Concrete Prepared with w/c Ratio of 0.3 and Cast at 25°C.

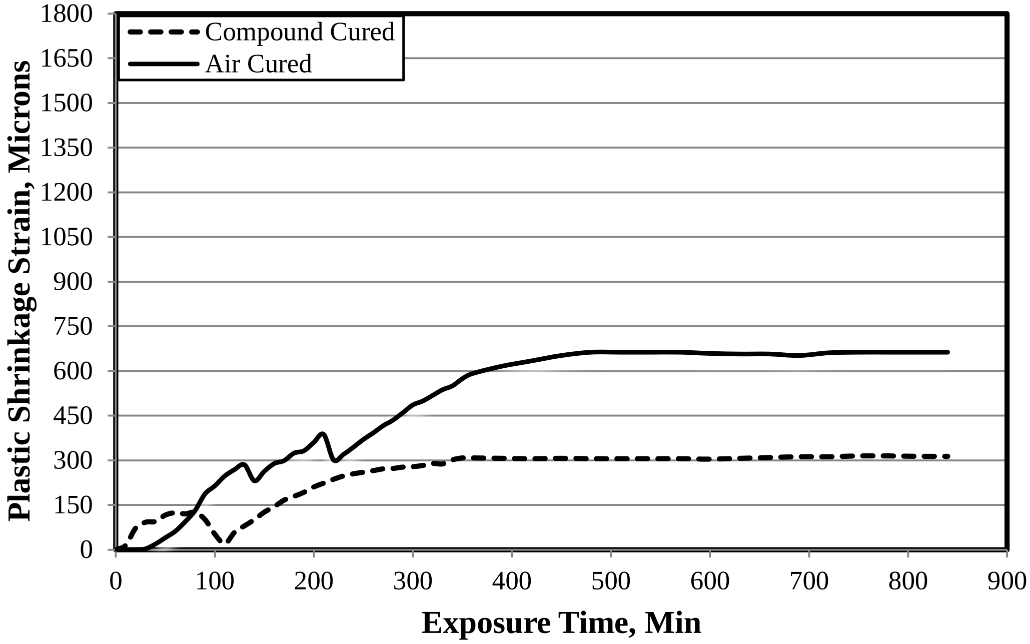

Figure 4.67: Plastic Shrinkage Strain in OPC Concrete Prepared with w/c Ratio of 0.3 and Cast at 32°C.

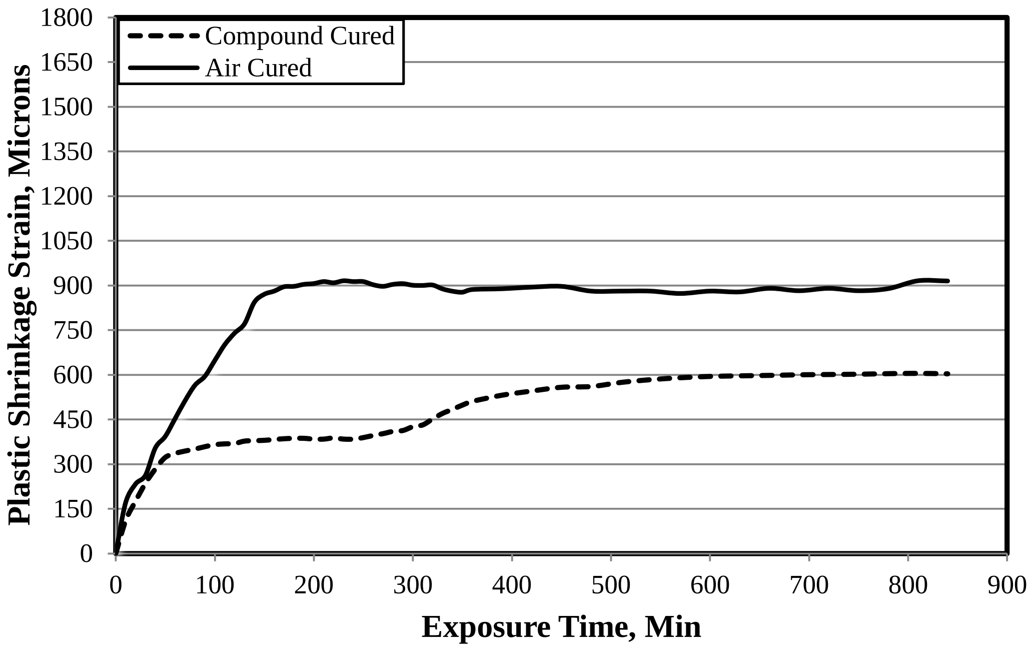

Figure 4.68: Plastic Shrinkage Strain in OPC Concrete Prepared with w/c Ratio of 0.3 and Cast at 38°C.

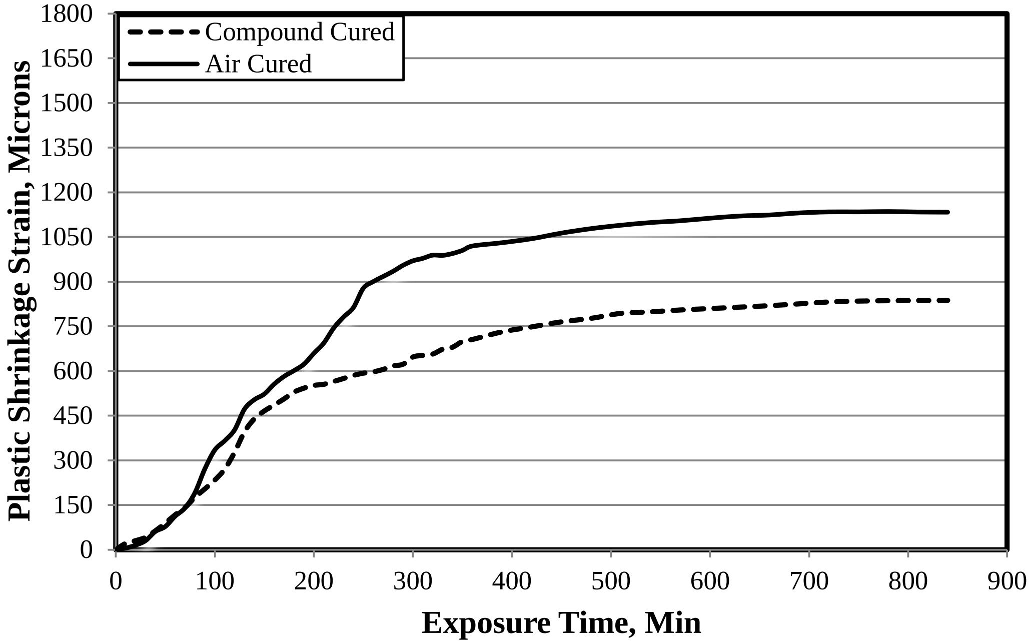

Figure 4.69: Plastic Shrinkage Strain in OPC Concrete Prepared with w/c Ratio of 0.3 and Cast at 45°C.

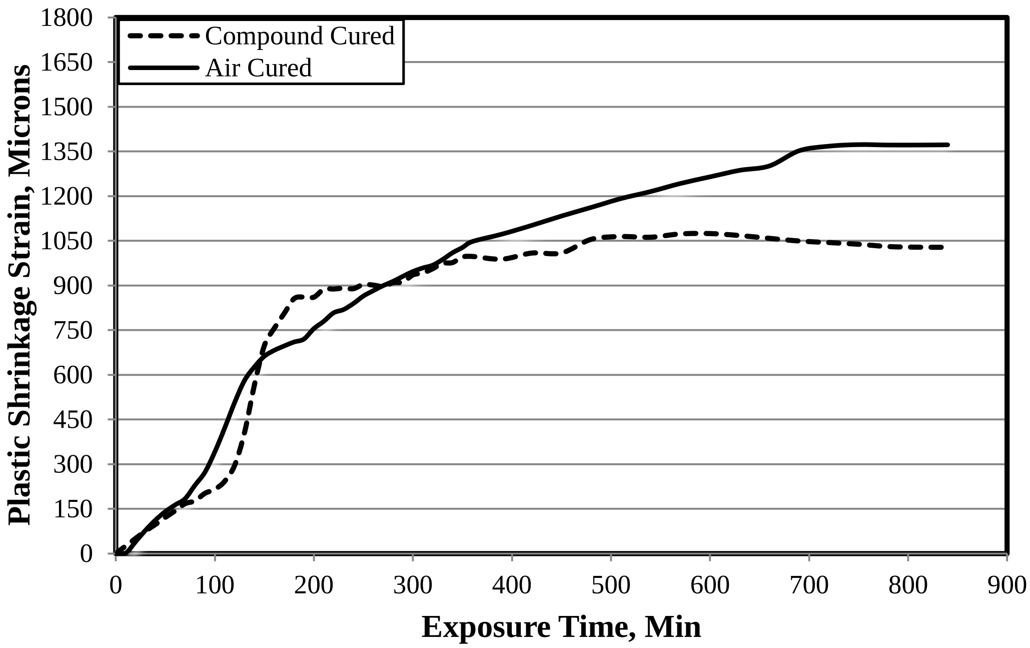

Figure 4.70: Plastic Shrinkage Strain in OPC Concrete Prepared with w/c Ratio of 0.4 and Cast at 25°C.

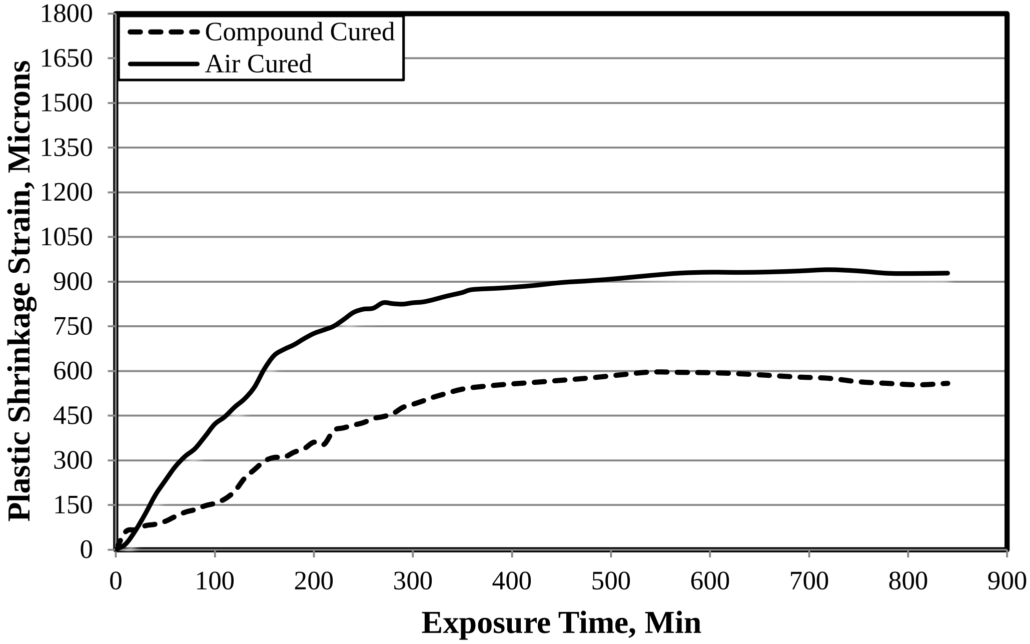

Figure 4.71: Plastic Shrinkage Strain in OPC Concrete Prepared with w/c Ratio of 0.4 and Cast at 32°C.

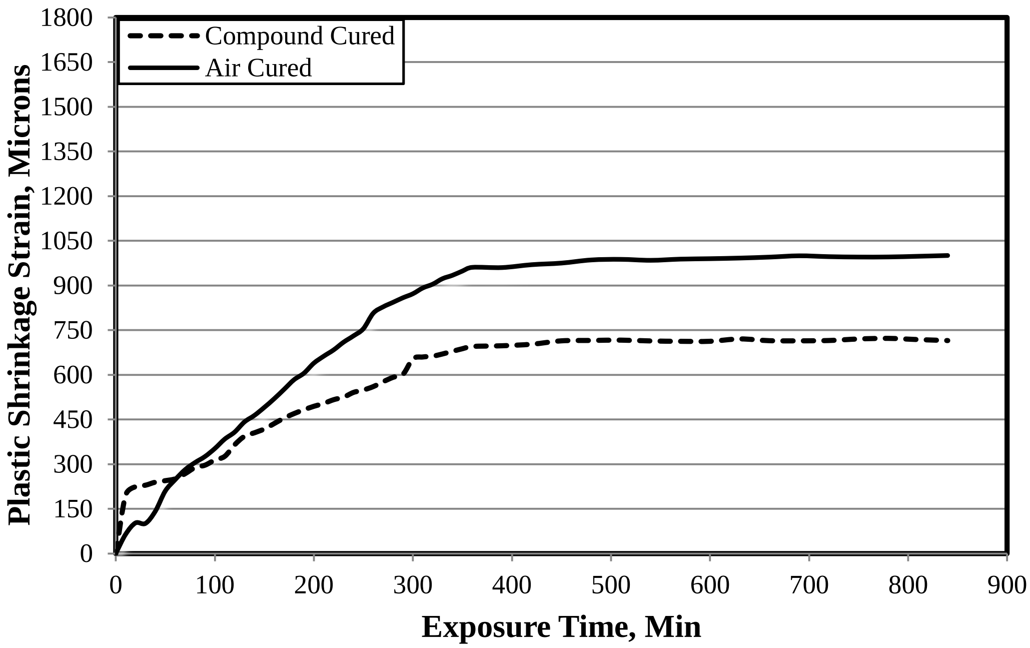

Figure 4.72: Plastic Shrinkage Strain in OPC Concrete Prepared with w/c Ratio of 0.4 and Cast at 38°C.

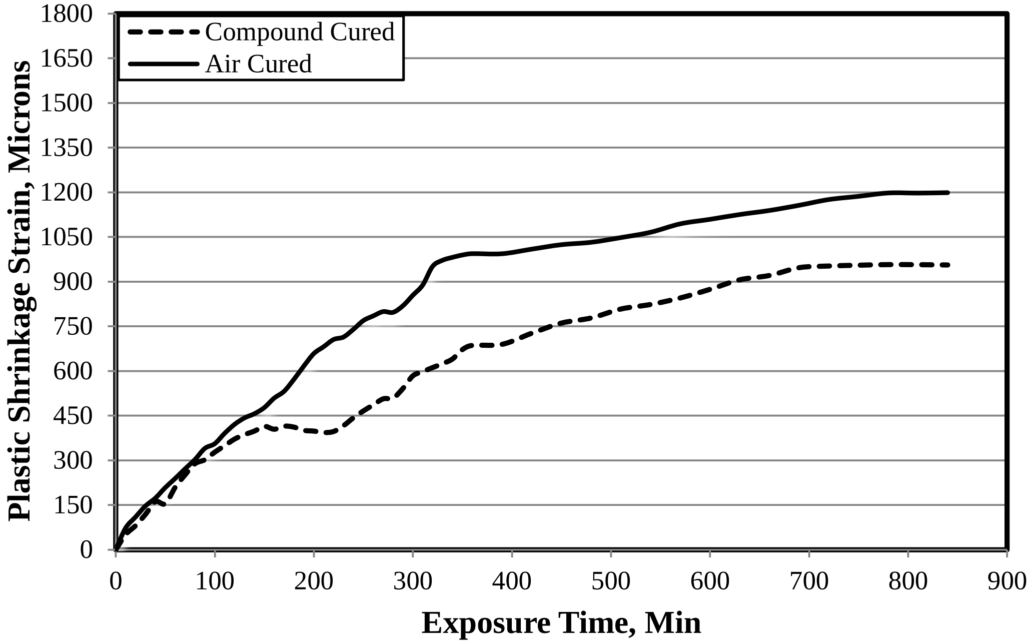

Figure 4.73: Plastic Shrinkage Strain in OPC Concrete Prepared with w/c Ratio of 0.4 and Cast at 45°C.

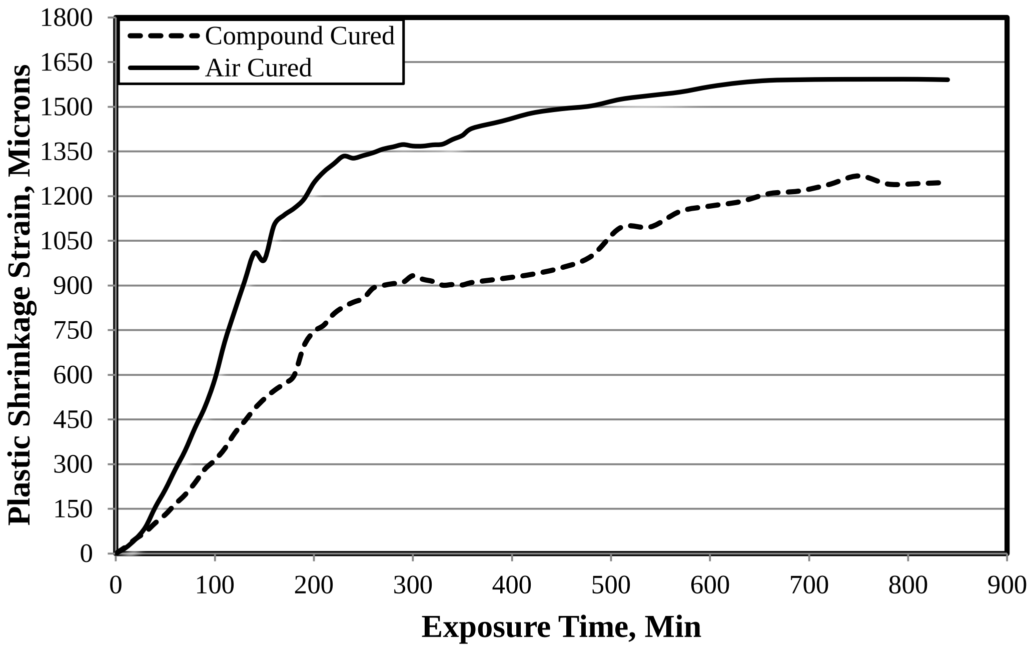

Figure 4.74: Plastic Shrinkage Strain in OPC Concrete Prepared with w/c Ratio of 0.45 and Cast at 25°C.

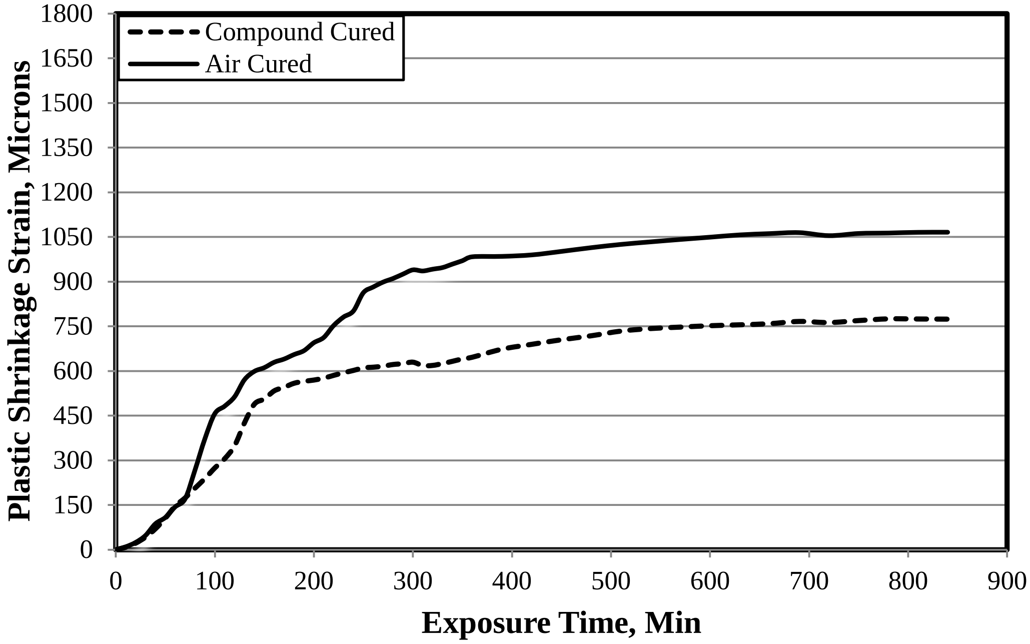

Figure 4.75: Plastic Shrinkage Strain in OPC Concrete Prepared with w/c Ratio of 0.45 and Cast at 32°C.

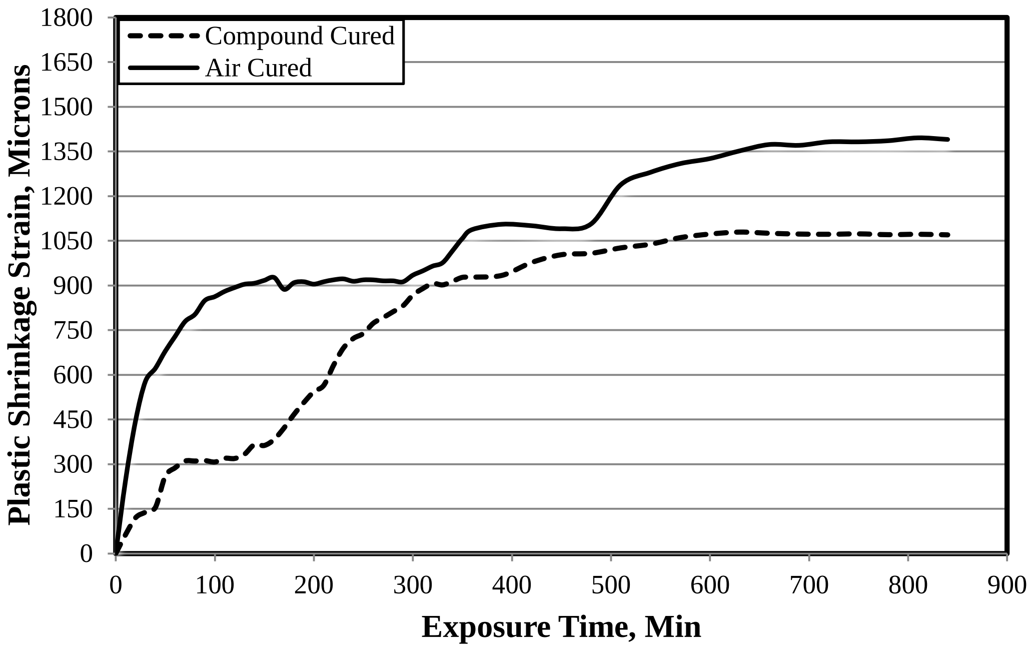

Figure 4.76: Plastic Shrinkage Strain in OPC Concrete Prepared with w/c Ratio of 0.45 and Cast at 38°C.

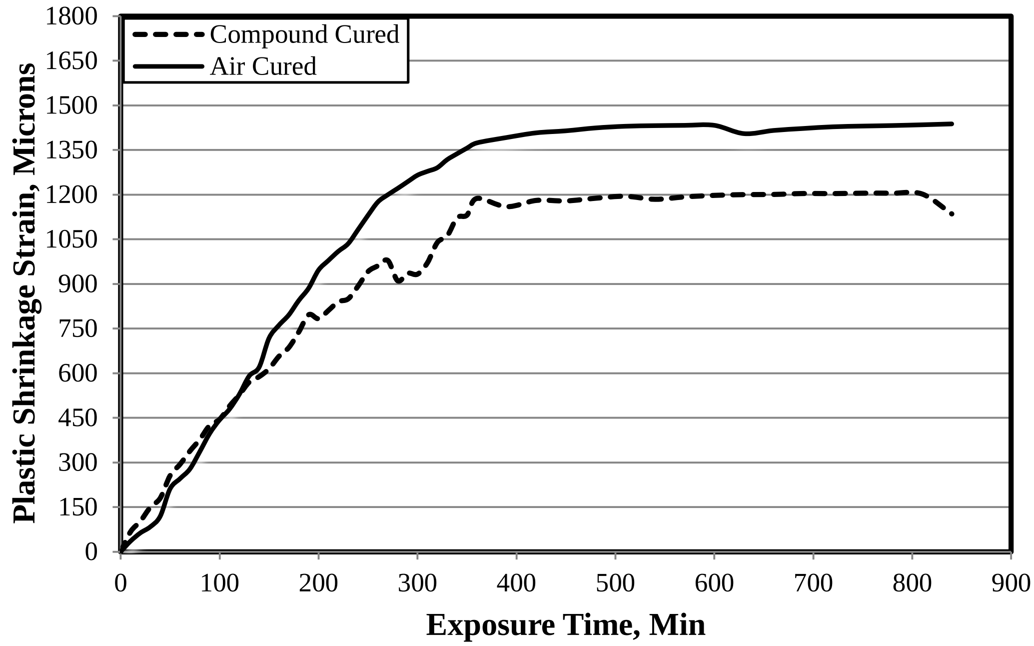

Figure 4.77: Plastic Shrinkage Strain in OPC Concrete Prepared with w/c Ratio of 0.45 and Cast at 45°C.

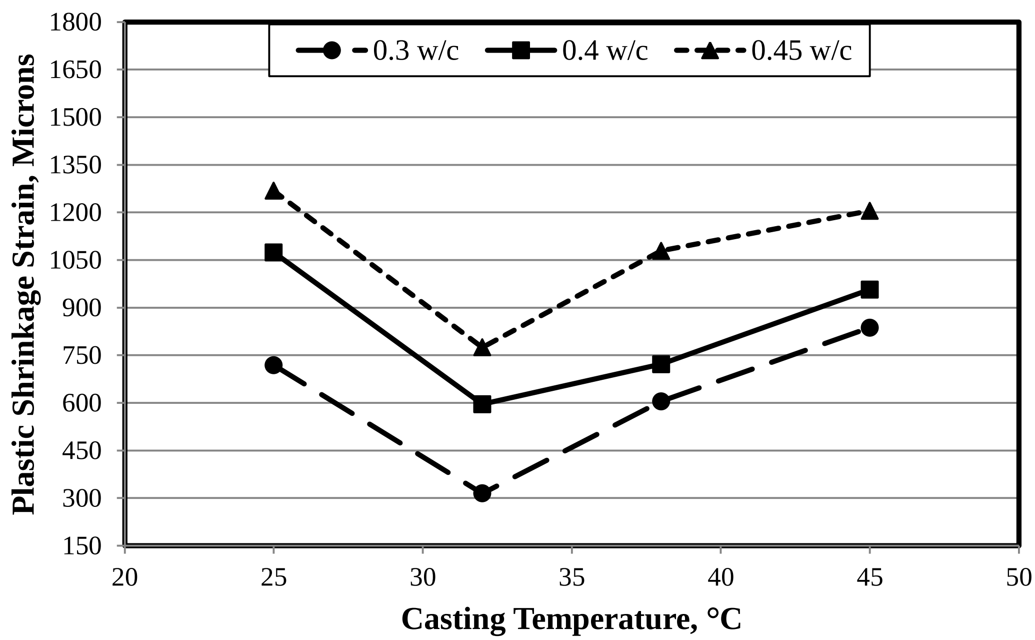

Figure 4.78: Maximum Plastic Shrinkage Strain in OPC Concretes Prepared with w/c Ratio of 0.3-0.45 and Cast at 25-45°C after Applying a Curing Compound.

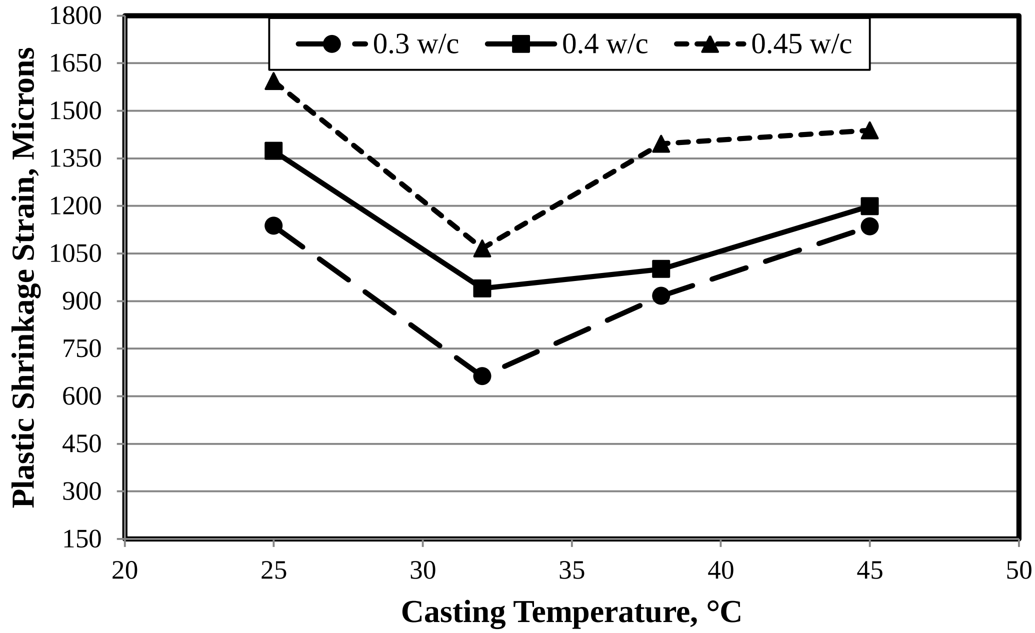

Figure 4.79: Maximum Plastic Shrinkage Strain in OPC Concretes Prepared with w/c Ratio of 0.3-0.45 and Cast at 25-45°C after Air Curing.

4.5.2 VFFA Cement Concrete

The variation of plastic shrinkage strain in VFFA cement concrete (OPC + 10% VFFA) specimens prepared with a w/cm ratio of 0.4, cast at 25, 32, 38 or 45°C and cured by applying a curing compound or covering with a plastic sheet on fresh concrete is depicted in Figures 4.80 through 4.83.

Effect of Curing Regime on Plastic Shrinkage Strain in VFFA Cement Concrete

The plastic shrinkage strain in the concrete specimens cured by applying a curing compound was less than that in the concrete specimens cured in air. For all casting temperatures, the maximum plastic shrinkage strain in the concrete specimens cured by applying a curing compound was on average 12.7% less than that in the air cured concrete specimens, as shown in Table 4.17. Al-Gahtani [7] reported that VFFA cement concrete exhibited about 22.0% less plastic shrinkage strain when cured with water-based curing membrane than cured by covering with a plastic sheet.

Effect of Casting Temperature on Plastic Shrinkage Strain in VFFA Cement Concrete

Despite the usage of any curing technique, 38°C was the optimum temperature at which the least value of maximum plastic shrinkage strain was observed in the concrete specimens followed by those that were cast at 32 and 45°C, while the highest shrinkage stain was recorded in the concrete specimens cast at 25°C, as shown in Table 4.17 and depicted in Figure 4.84. On average, the maximum plastic shrinkage strain in the concrete specimens cast at 38°C was 51.7, 23.7 and 36.5% less than that in the concrete specimens cast at 25, 32 or 45°C, respectively.

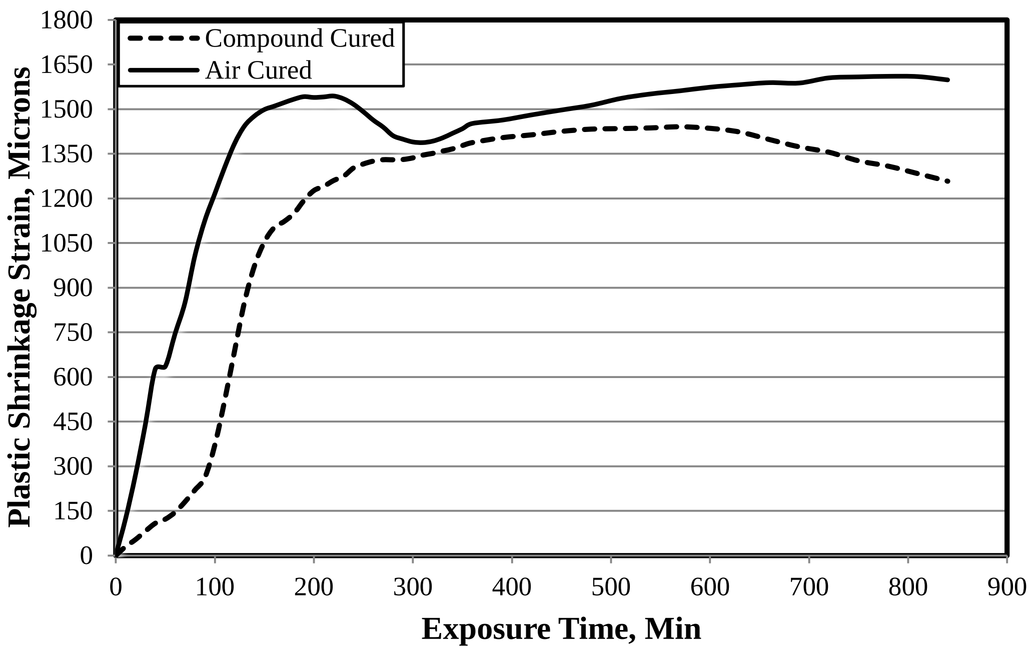

Figure 4.80: Plastic Shrinkage Strain in VFFA Cement Concrete Prepared with w/cm Ratio of 0.4 and Cast at 25°C.

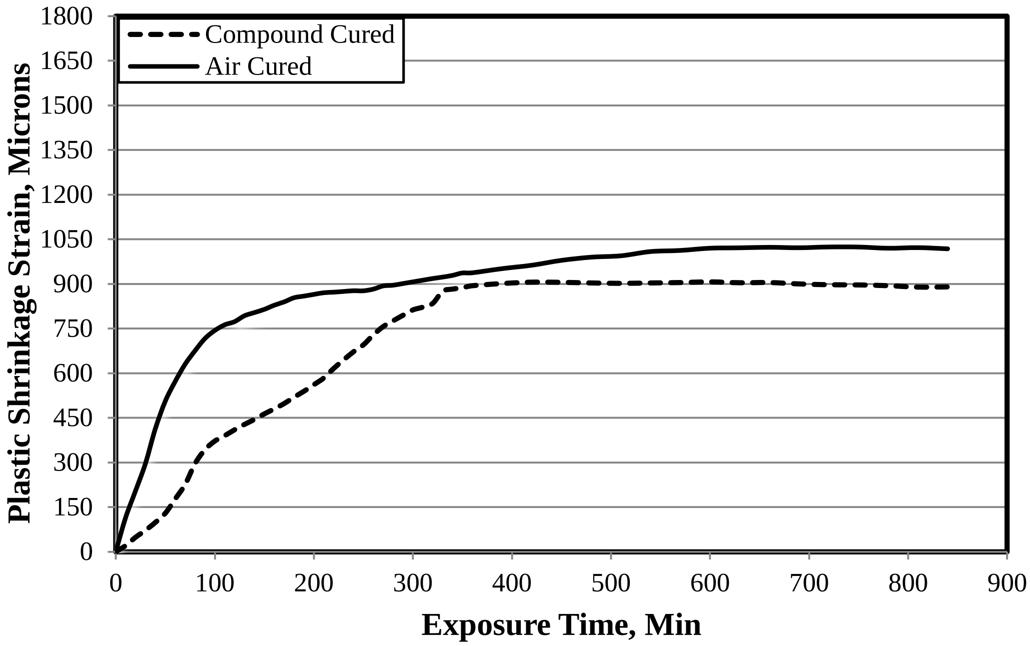

Figure 4.81: Plastic Shrinkage Strain in VFFA Cement Concrete Prepared with w/cm Ratio of 0.4 and Cast at 32°C.

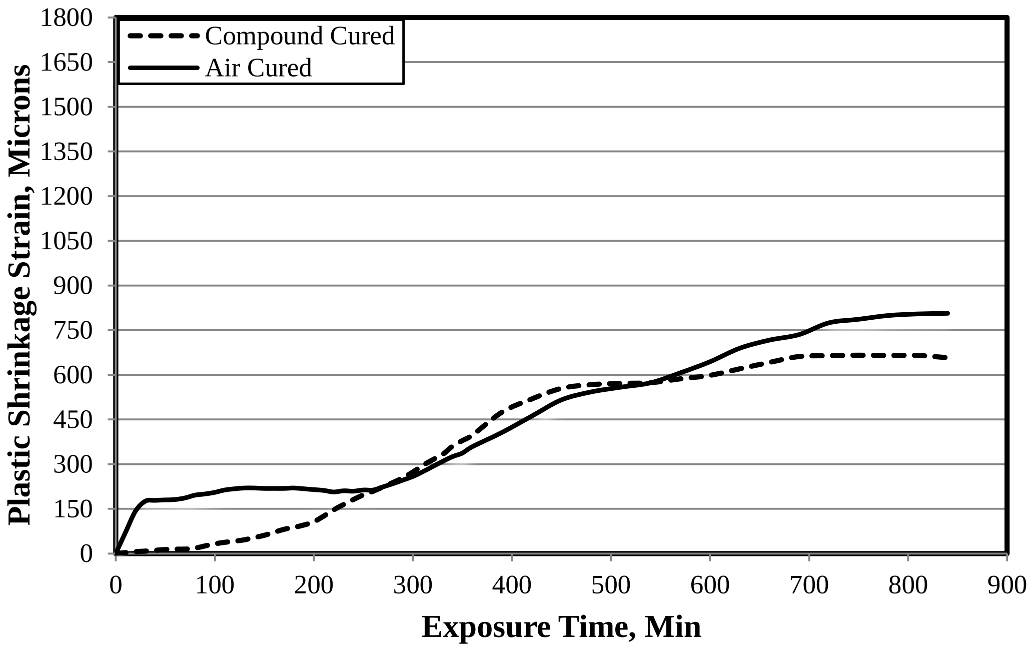

Figure 4.82: Plastic Shrinkage Strain in VFFA Cement Concrete Prepared with w/cm Ratio of 0.4 and Cast at 38°C.

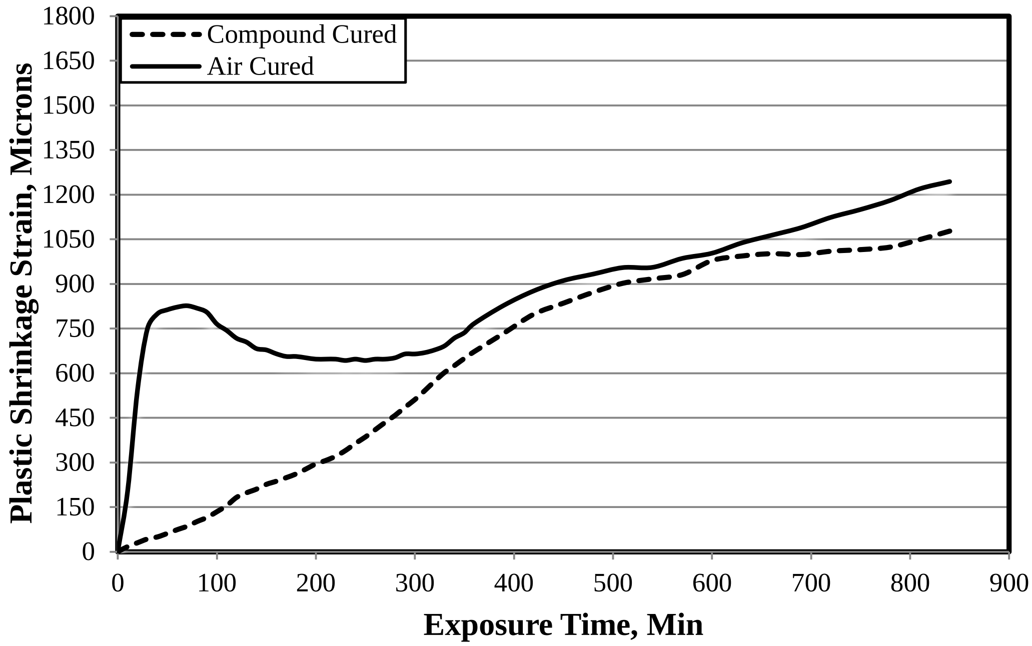

Figure 4.83: Plastic Shrinkage Strain in VFFA Cement Concrete Prepared with w/cm Ratio of 0.4 and Cast at 45°C.

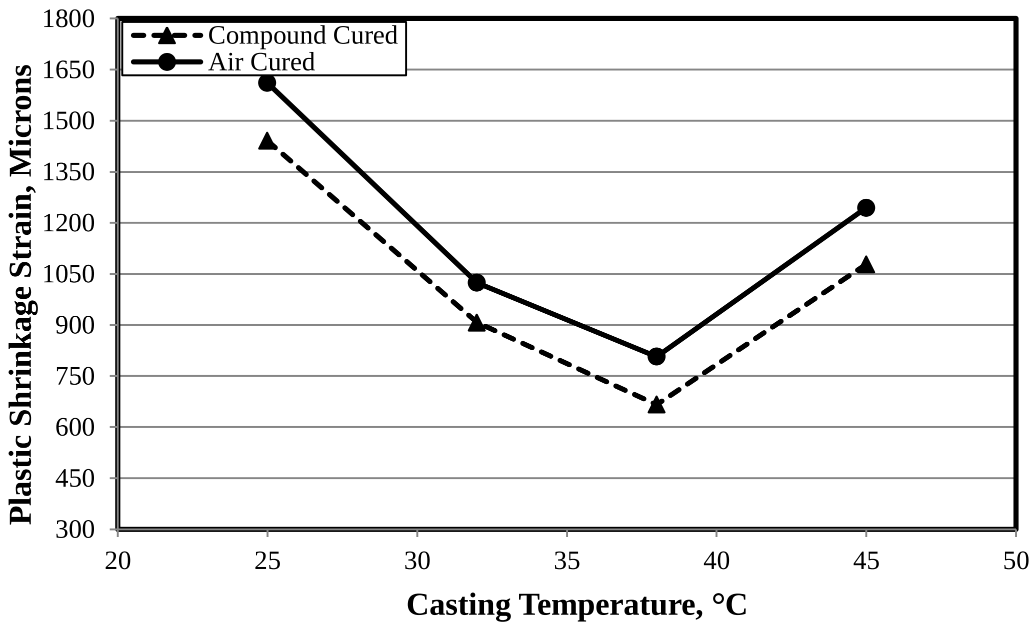

Figure 4.84: Maximum Plastic Shrinkage Strain in VFFA Cement Concretes.

4.5.3 FA Cement Concrete

The effect of partial replacement of OPC by 30% FA cement on the plastic shrinkage strain is discussed in this section. For each curing regime, the data of the plastic shrinkage strain and exposure time were plotted for all the concrete specimens prepared at a constant w/cm ratio of 0.4 and cast at varying temperatures of 25 to 45°C, as shown in Figures 4.85 through 4.88.

Effect of Curing Regime on Plastic Shrinkage Strain in FA Cement Concrete

From Table 4.17, the maximum plastic shrinkage strain in the concrete specimens cured by applying a curing compound was on average 27.2% less than that in the concrete specimens cured in air by covering with a plastic sheet. Al-Gahtani [7] also reported that FA cement concrete specimens attained about 26.0% lower plastic shrinkage strain when cured with water-based curing compound compared with that cured by covering with a plastic sheet. The use of fly ash involves greater plastic shrinkage thereby increasing the vulnerability of the concrete to plastic shrinkage cracking and, hence, extra care should be taken in order to prevent such cracking by protecting the fresh concrete from drying as soon as possible after being placed and finished [61].

Effect of Casting Temperature on Plastic Shrinkage Strain in FA Cement Concrete

For all the curing regimes, the smallest amount of maximum plastic shrinkage strain was recorded in the concrete specimens cast at 38°C followed by those that were cast at 45°C while the highest shrinkage stain was observed in the concrete specimens cast at 25°C, as shown in Table 4.17 and depicted in Figure 4.89. On average, the maximum plastic shrinkage strain in the concrete specimens cast at 38°C was 46.5, 39.9 and 17.9% less than that in the concrete specimens cast at 25, 32 or 45°C, respectively.

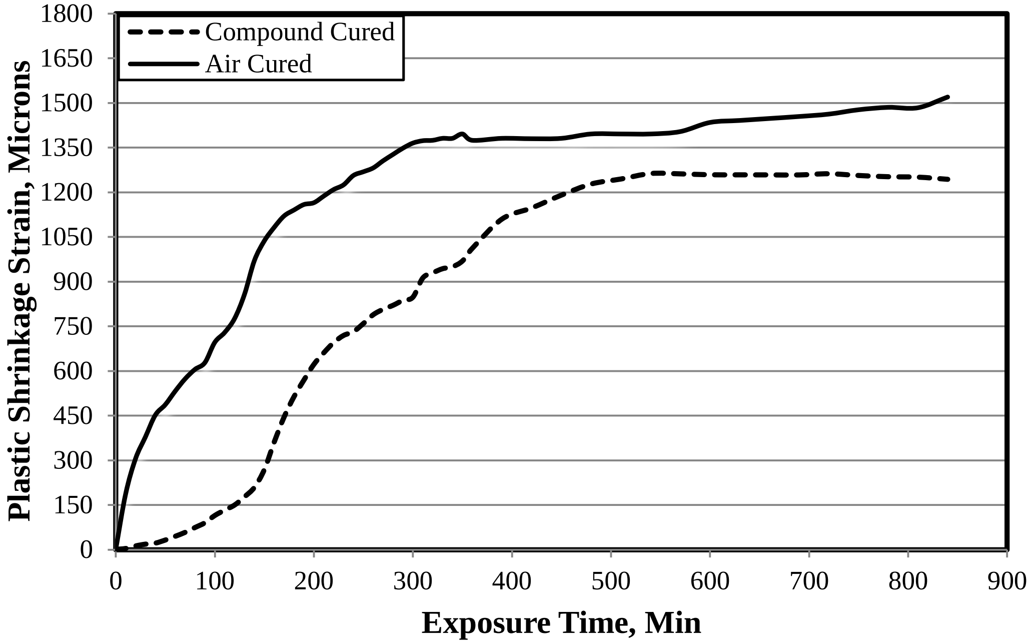

Figure 4.85: Plastic Shrinkage Strain in FA Cement Concrete Prepared with w/cm Ratio of 0.4 and Cast at 25°C.

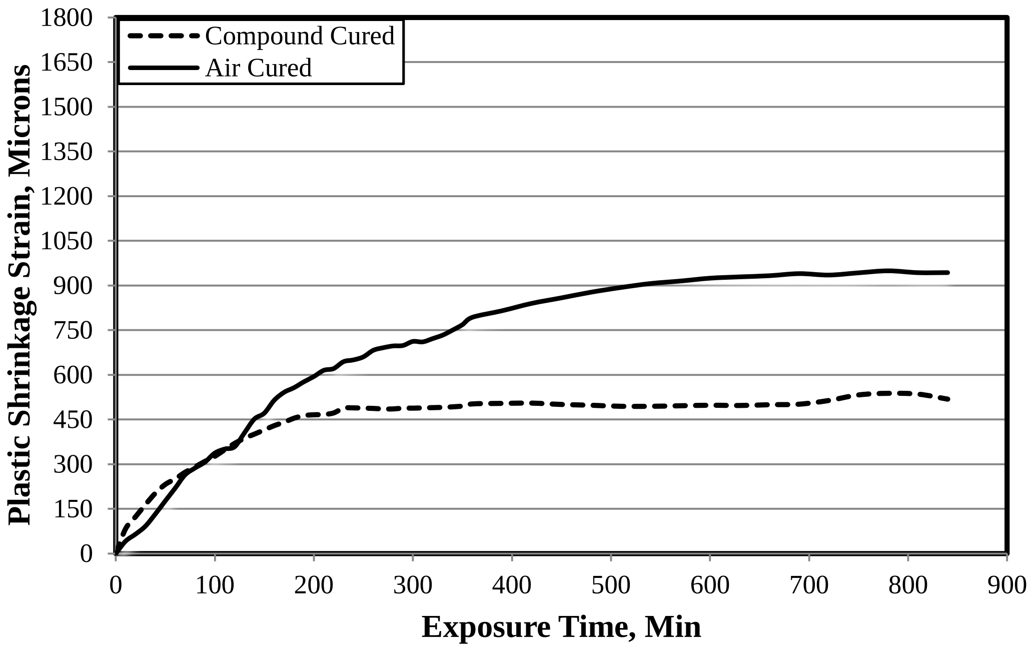

Figure 4.86: Plastic Shrinkage Strain in FA Cement Concrete Prepared with w/cm Ratio of 0.4 and Cast at 32°C.

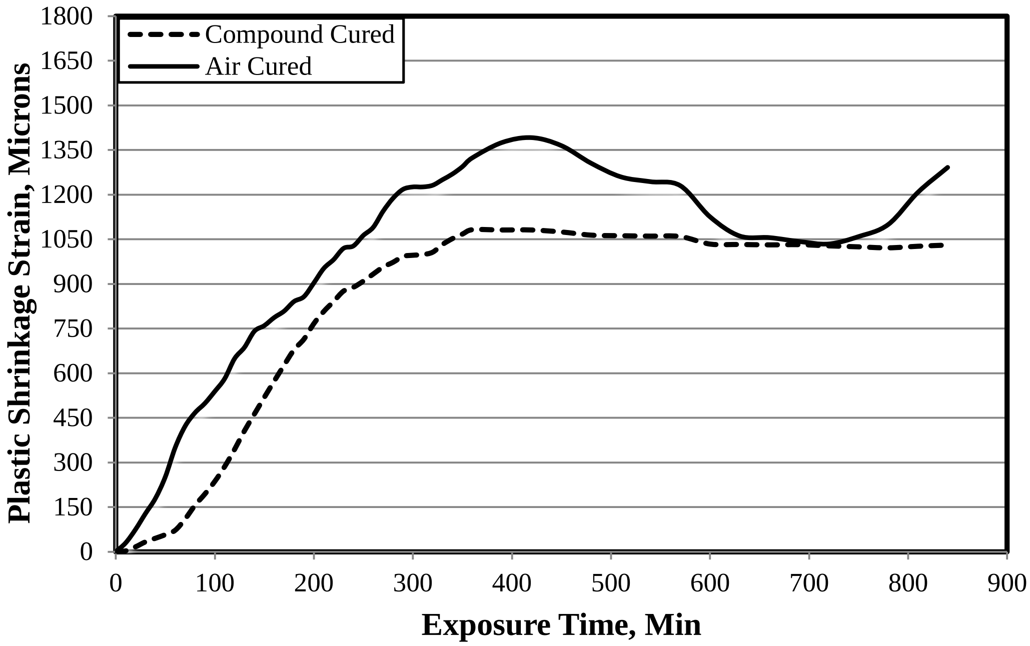

Figure 4.87: Plastic Shrinkage Strain in FA Cement Concrete Prepared with w/cm Ratio of 0.4 and Cast at 38°C.

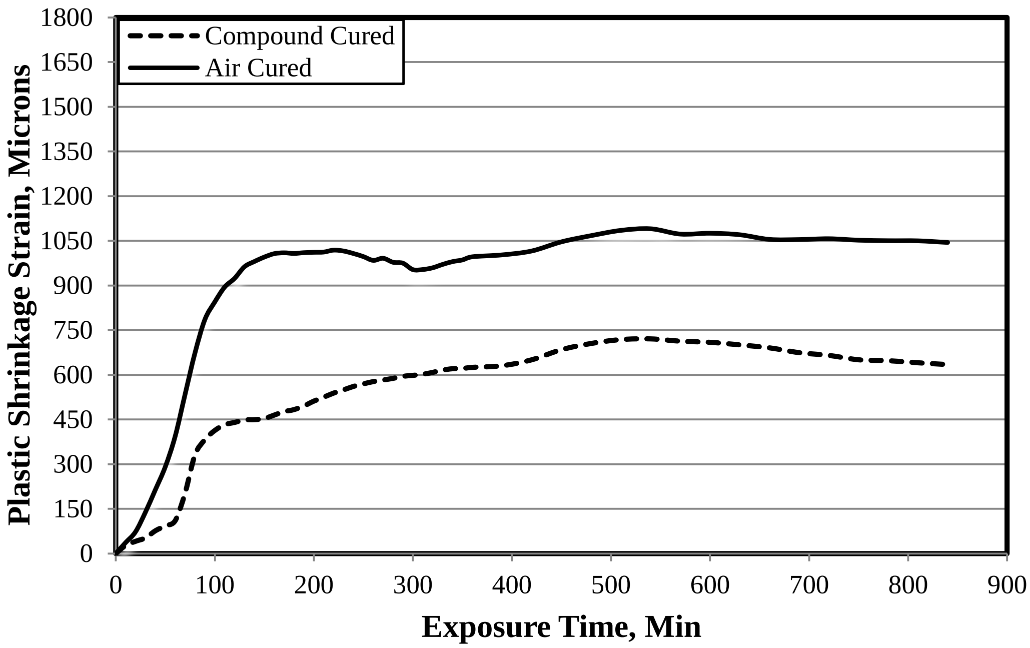

Figure 4.88: Plastic Shrinkage Strain in FA Cement Concrete Prepared with w/cm Ratio of 0.4 and Cast at 45°C.

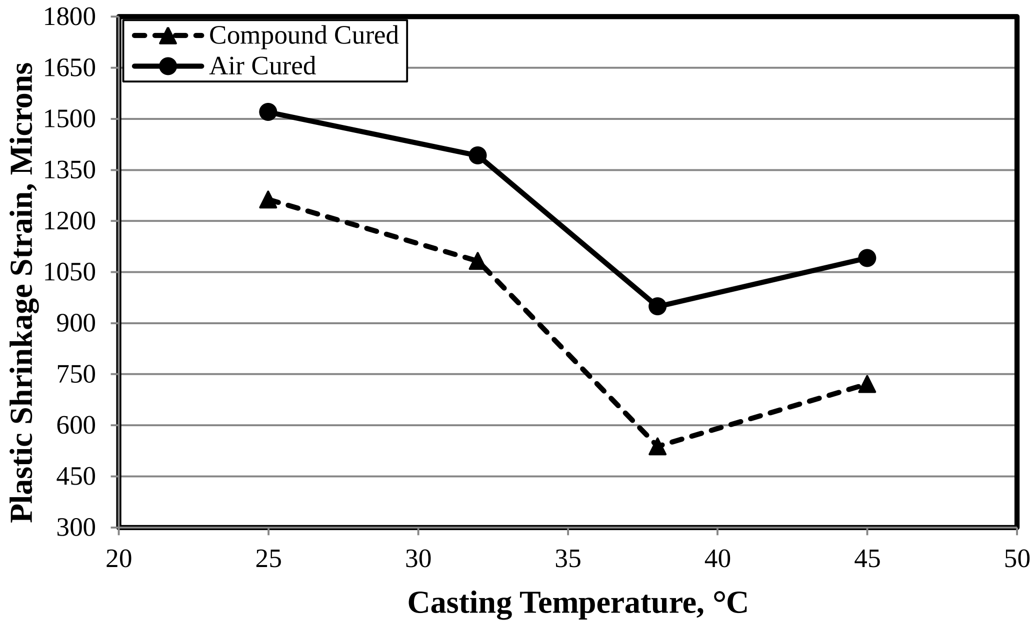

Figure 4.89: Maximum Plastic Shrinkage Strain in FA Cement Concretes.

4.5.4 SF Cement Concrete

The plastic shrinkage strain in SF cement concrete (OPC + 7% SF) specimens prepared with a constant w/cm ratio of 0.4, cast at range of temperature of 25 to 45°C and cured by applying a curing compound or covering with a plastic sheet is depicted in Figures 4.90 through 4.93.

Effect of Curing Regime on Plastic Shrinkage Strain in SF Cement Concrete

On average, the maximum plastic shrinkage strain in the concrete specimens cured by application of a curing compound was 17.9% less than that in the air cured concrete specimens, as shown in Table 4.17. Maslehuddin et al. [79] showed that SF cement concrete exhibited about 22% lesser plastic shrinkage strain when cured with water-based curing compound as compared to curing by covering with a plastic sheet. Due to the high pozzolanic reactivity of silica fume, the chances of plastic and drying shrinkage of such concrete is also increased if it is inadequately cured [50,51].

Effect of Casting Temperature on Plastic Shrinkage Strain in SF Cement Concrete

Regardless of the curing regime, the least value of maximum plastic shrinkage strain was recorded in the concrete specimens cast at 38°C followed by those that were cast at 45°C, while the highest shrinkage stain was noted in the concrete specimens cast at 25°C and it was comparable to those cast 32°C, as shown in Table 4.17 and depicted in Figure 4.94. On average, the maximum plastic shrinkage strain in the concrete specimens cast at 38°C was 35.5, 32.3 and 16.6% less than that in the concrete specimens cast at 25, 32 or 45°C, respectively.

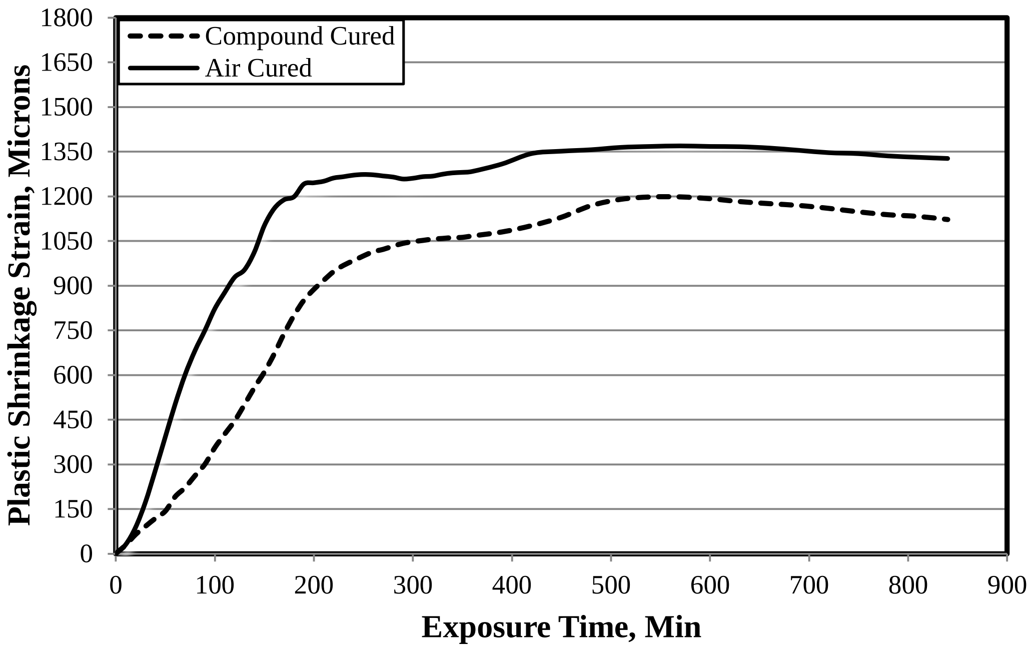

Figure 4.90: Plastic Shrinkage Strain in SF Cement Concrete Prepared with w/cm Ratio of 0.4 and Cast at 25°C.

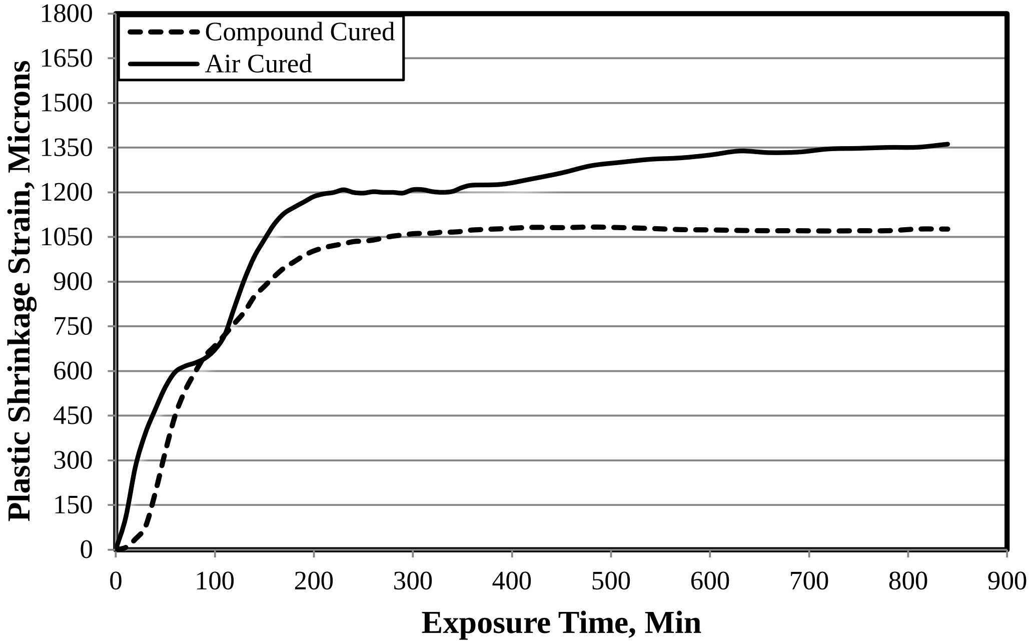

Figure 4.91: Plastic Shrinkage Strain in SF Cement Concrete Prepared with w/cm Ratio of 0.4 and Cast at 32°C.

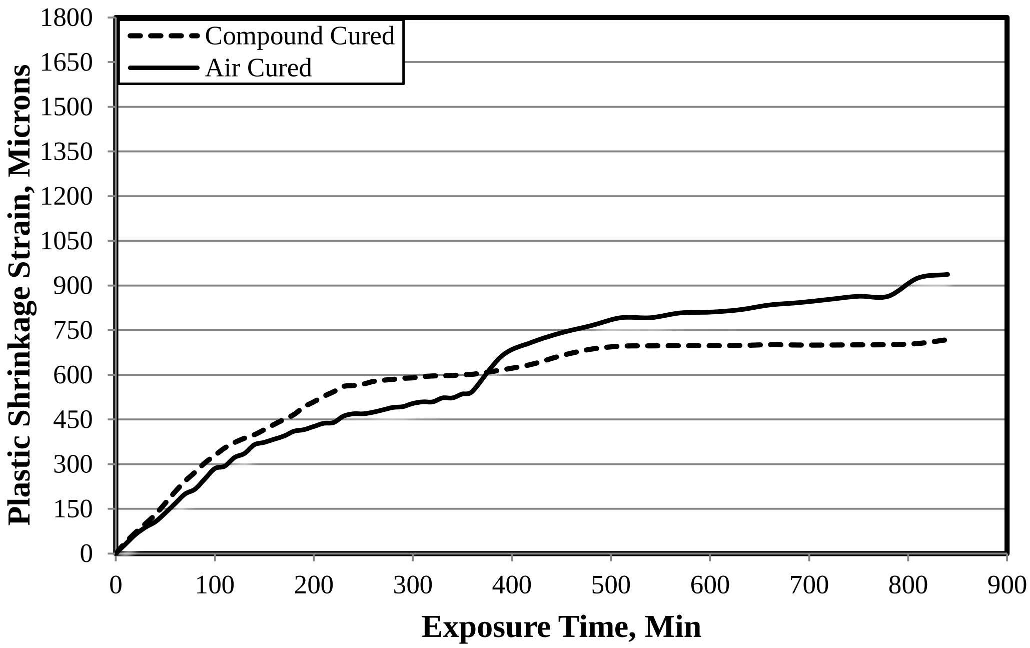

Figure 4.92: Plastic Shrinkage Strain in SF Cement Concrete Prepared with w/cm Ratio of 0.4 and Cast at 38°C.

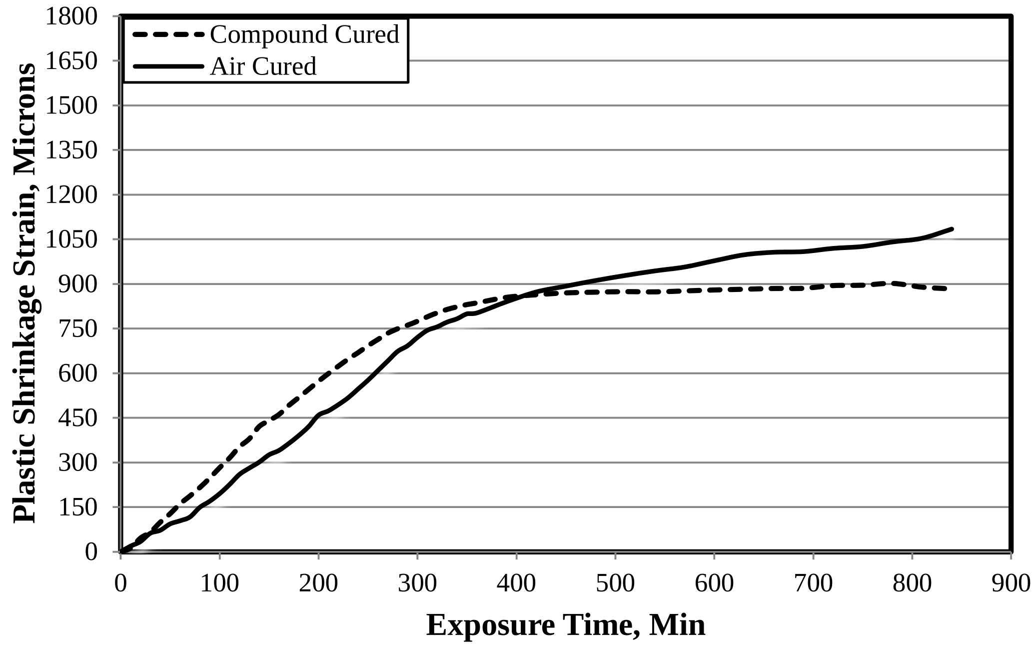

Figure 4.93: Plastic Shrinkage Strain in SF Cement Concrete Prepared with w/cm Ratio of 0.4 and Cast at 45°C.

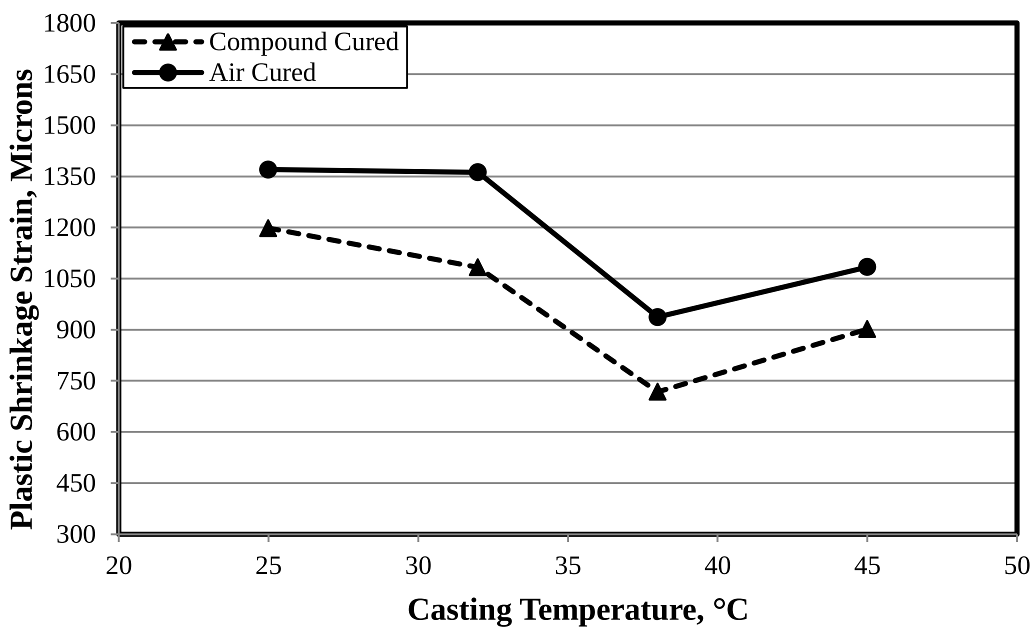

Figure 4.94: Maximum Plastic Shrinkage Strain in SF Cement Concretes.

4.5.5 GGBFS Cement Concrete

The plastic shrinkage strain in GGBFS cement concrete (OPC + 70% GGBFS) specimens prepared with a w/cm ratio of 0.4, cast at varying temperatures of 25 to 45°C and cured by application of a curing compound or covering with a plastic sheet is depicted in Figures 4.95 through 4.98.

Effect of Curing Regime on Plastic Shrinkage Strain in GGBFS Cement Concrete

The maximum plastic shrinkage strain in the concrete specimens cured by applying a curing compound was on average 20.2% less than that in the concrete specimens cured in air, as shown in Table 4.17.

Effect of Casting Temperature on Plastic Shrinkage Strain in GGBFS Cement Concrete

For all the curing techniques utilized, the least value of maximum plastic shrinkage strain was recorded in the concrete specimens cast at 45°C (comparable to strain at 38°C), while the shrinkage strain increased with a reduction in casting temperature such that the highest shrinkage stain was observed in the concrete specimens cast at 25°C, as shown in Table 4.17 and depicted in Figure 4.99. On average, the maximum plastic shrinkage strain in the concrete specimens cast at 45°C was 39.7, 21.7 and 4.8% less than that in the concrete specimens cast at 25, 32 or 38°C, respectively. The reason for the lowest shrinkage of GGBFS cement concrete at the highest casting temperature of 45°C could be ascribed to the fact that the higher temperature was highly beneficial in increasing the strength (both compressive and tensile) of GGBFS concrete thereby resisting the development of plastic shrinkage.

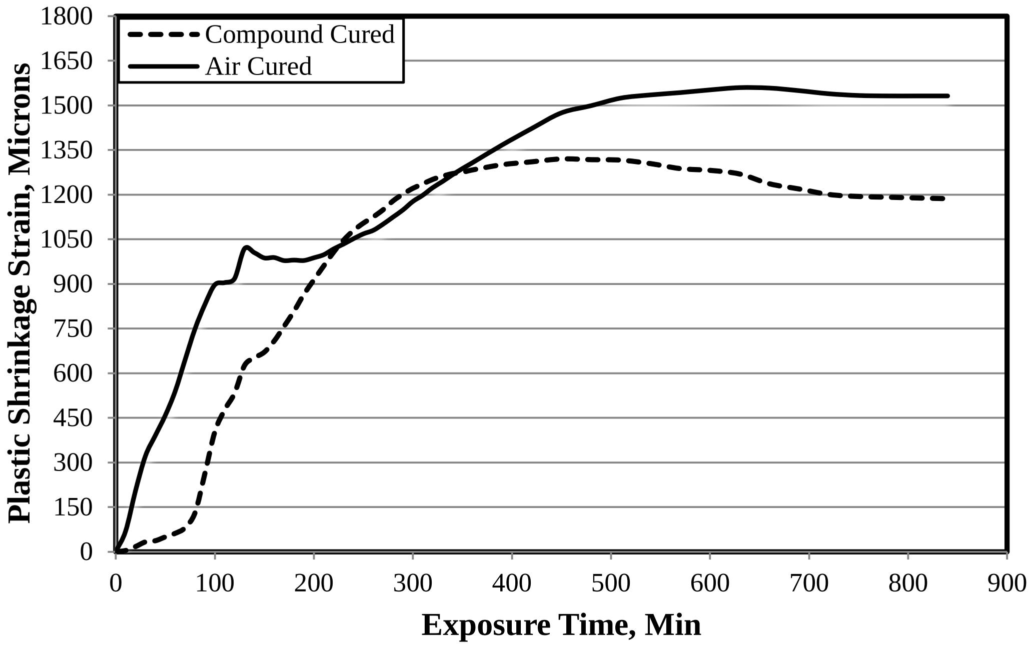

Figure 4.95: Plastic Shrinkage Strain in GGBFS Cement Concrete Prepared with w/cm Ratio of 0.4 and Cast at 25°C.

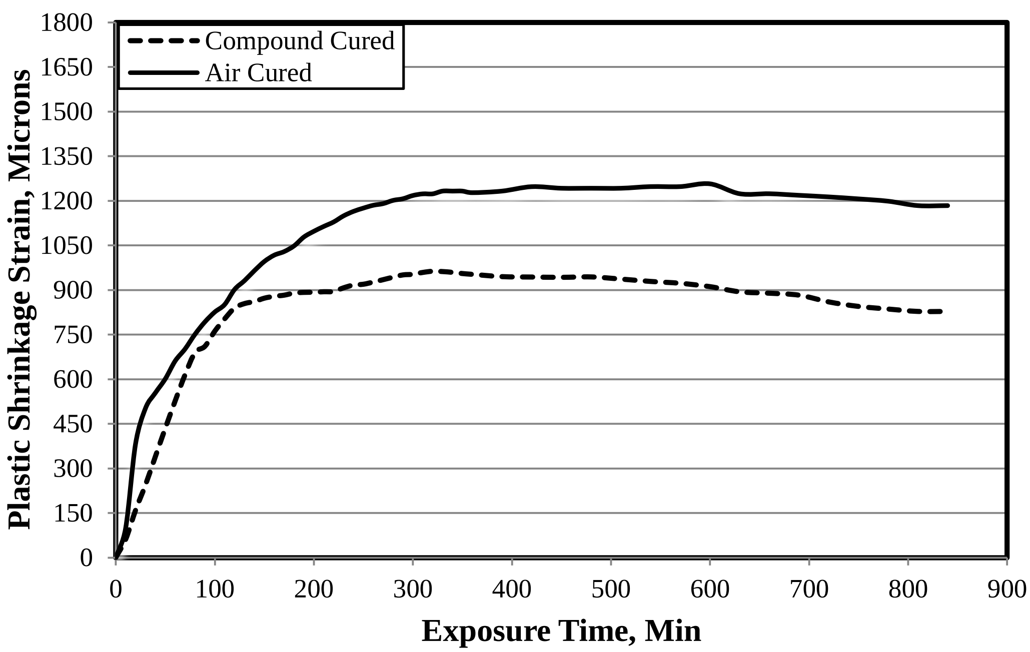

Figure 4.96: Plastic Shrinkage Strain in GGBFS Cement Concrete Prepared with w/cm Ratio of 0.4 and Cast at 32°C.

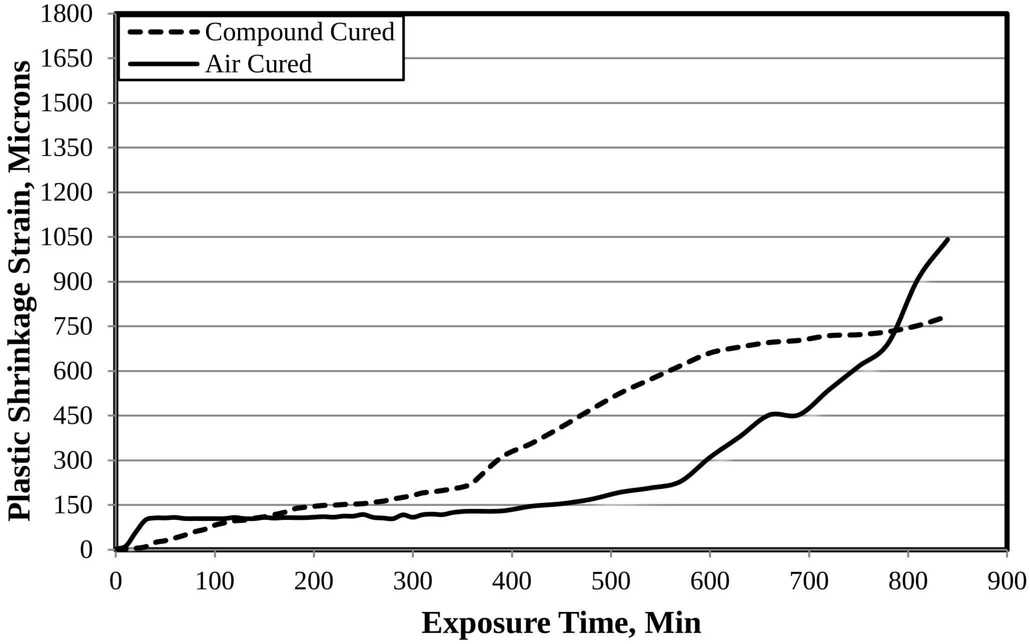

Figure 4.97: Plastic Shrinkage Strain in GGBFS Cement Concrete Prepared with w/cm Ratio of 0.4 and Cast at 38°C.

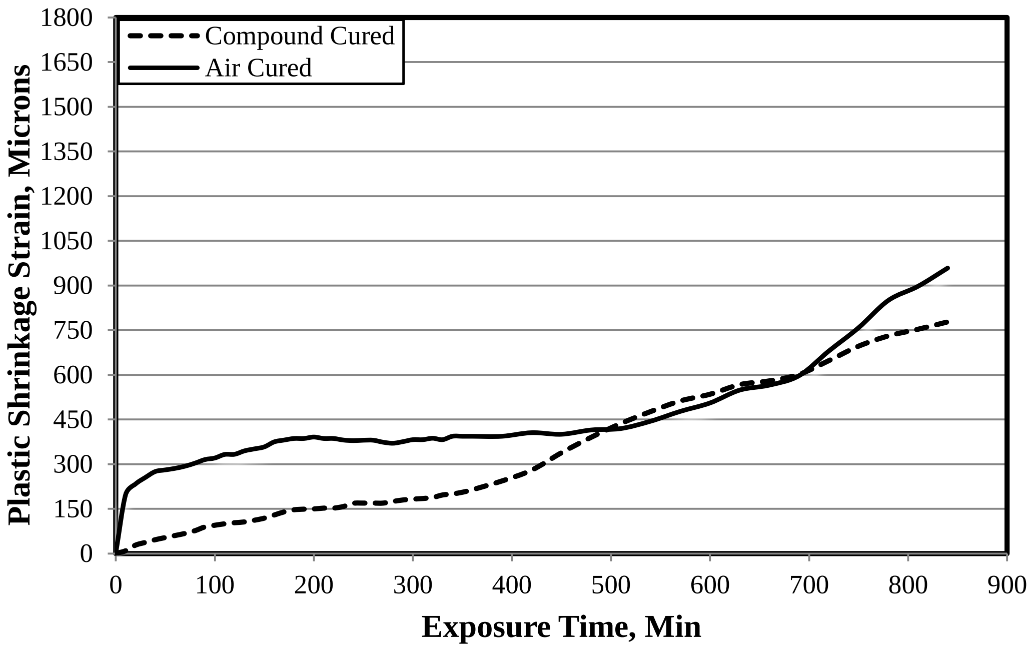

Figure 4.98: Plastic Shrinkage Strain in GGBFS Cement Concrete Prepared with w/cm Ratio of 0.4 and Cast at 45°C.

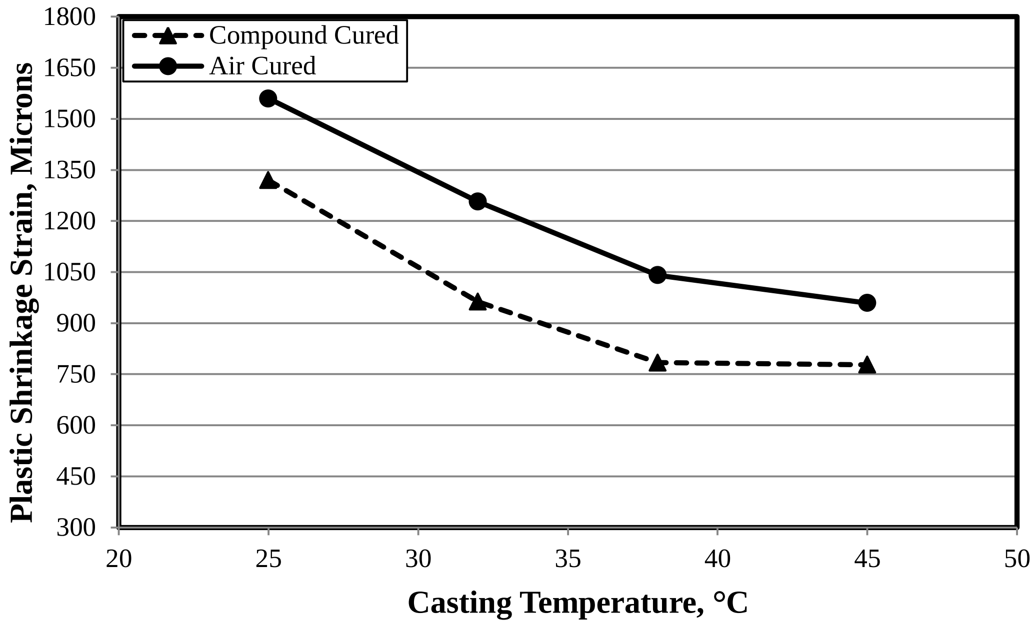

Figure 4.99: Maximum Plastic Shrinkage Strain in GGBFS Cement Concretes.

4.5.6 NP Cement Concrete

The influence of partial replacement of OPC by 20% NP cement on the plastic shrinkage strain is discussed in this section. For each curing technique utilized, the data of the plastic shrinkage strain were plotted against the exposure time for all the concrete specimens prepared at a constant w/cm ratio of 0.4 and cast at range of temperatures of 25 to 45°C, as shown in Figures 4.100 through 4.103.

Effect of Curing Regime on Plastic Shrinkage Strain in NP Cement Concrete

From Table 4.17, the maximum plastic shrinkage strain in the concrete specimens cured by applying a curing compound was on average 15.2% less than that in the air cured concrete specimens.

Effect of Casting Temperature on Plastic Shrinkage Strain in NP Cement Concrete

Irrespective of the curing regime used, the least amount of maximum plastic shrinkage strain was recorded in the concrete specimens cast at 38°C followed by those that were cast at 32 or 45°C, while the highest shrinkage stain was observed in the concrete specimens cast at 25°C, as shown in Table 4.17 and depicted in Figure 4.104. On average, the maximum plastic shrinkage strain in the concrete specimens cast at 38°C was 40.8, 29.6 and 27.7% less than that in the concrete specimens cast at 25, 32 or 45°C, respectively.

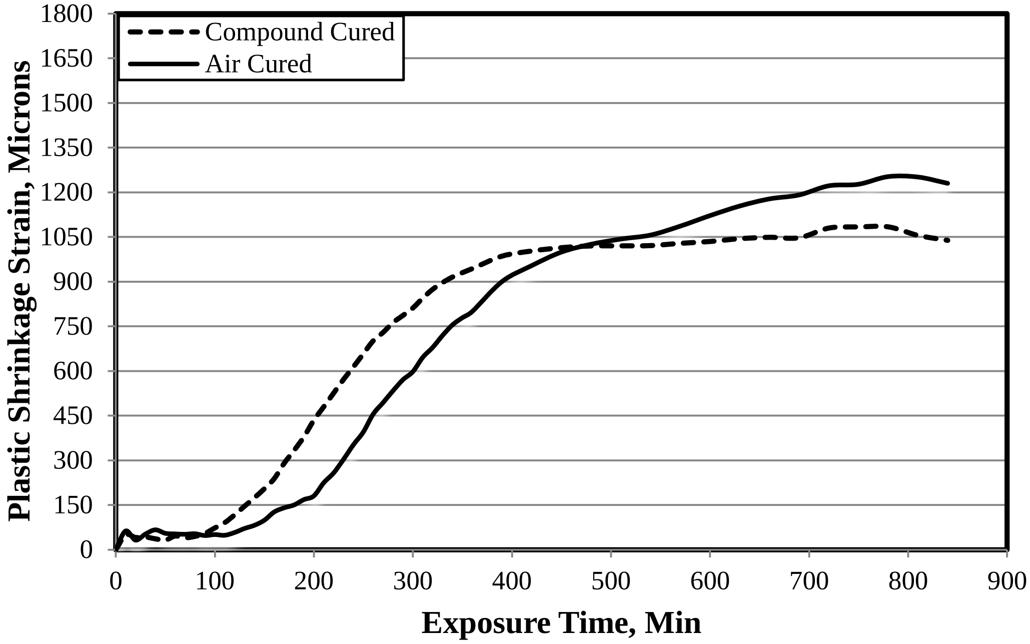

Figure 4.100: Plastic Shrinkage Strain in NP Cement Concrete Prepared with w/cm Ratio of 0.4 and Cast at 25°C.

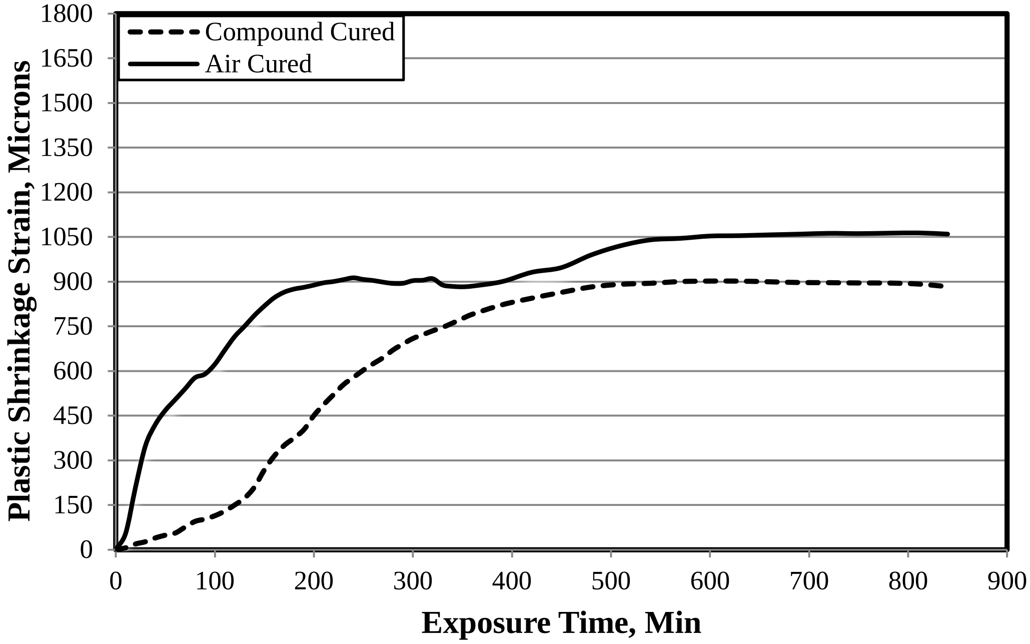

Figure 4.101: Plastic Shrinkage Strain in NP Cement Concrete Prepared with w/cm Ratio of 0.4 and Cast at 32°C.

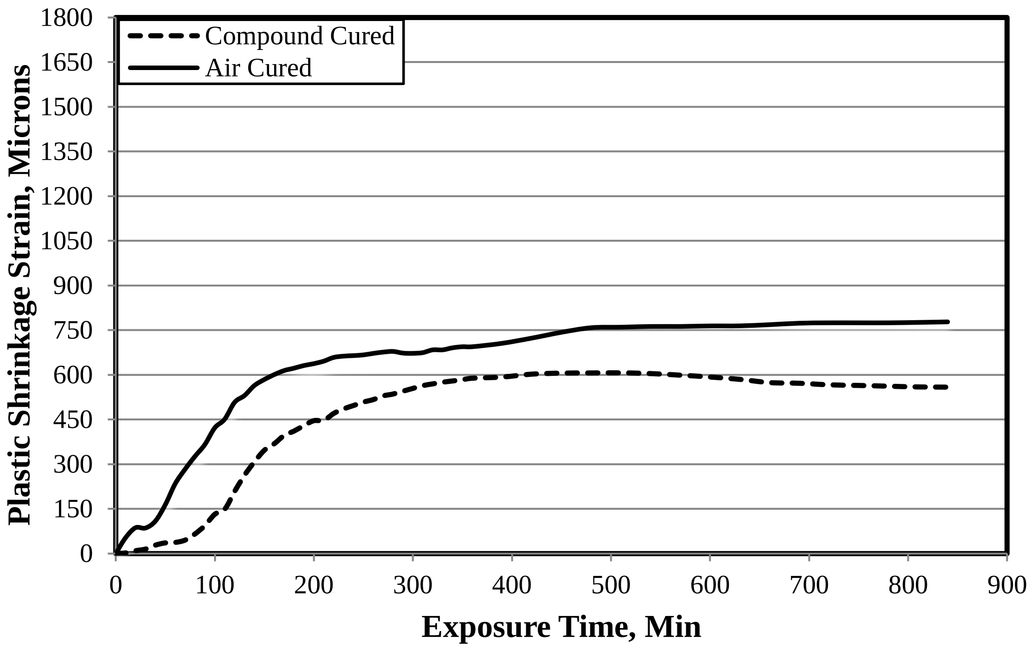

Figure 4.102: Plastic Shrinkage Strain in NP Cement Concrete Prepared with w/cm Ratio of 0.4 and Cast at 38°C.

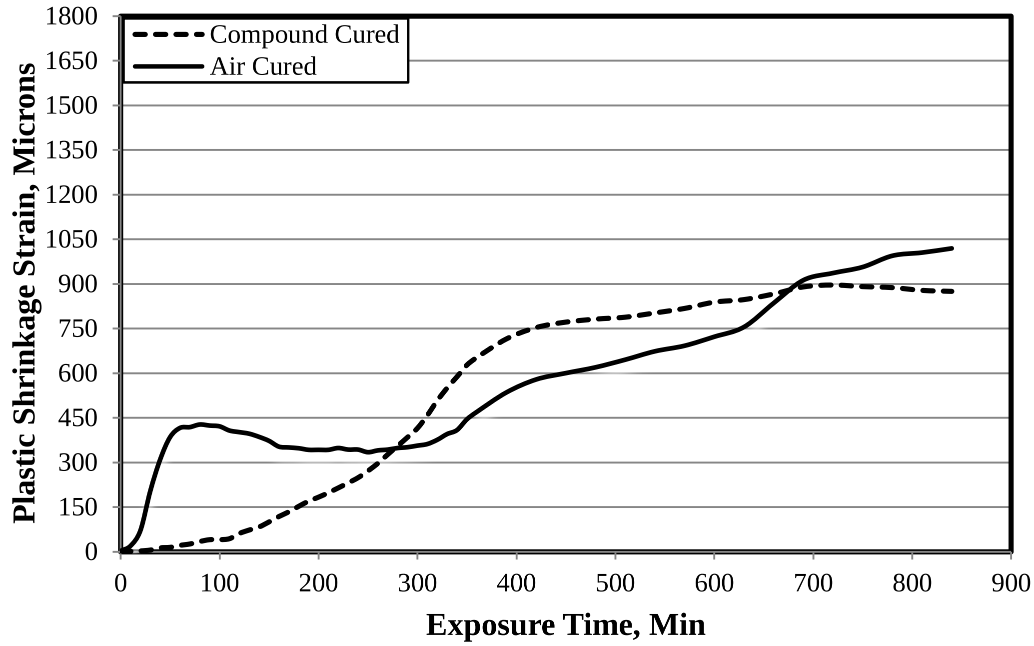

Figure 4.103: Plastic Shrinkage Strain in NP Cement Concrete Prepared with w/cm Ratio of 0.4 and Cast at 45°C.

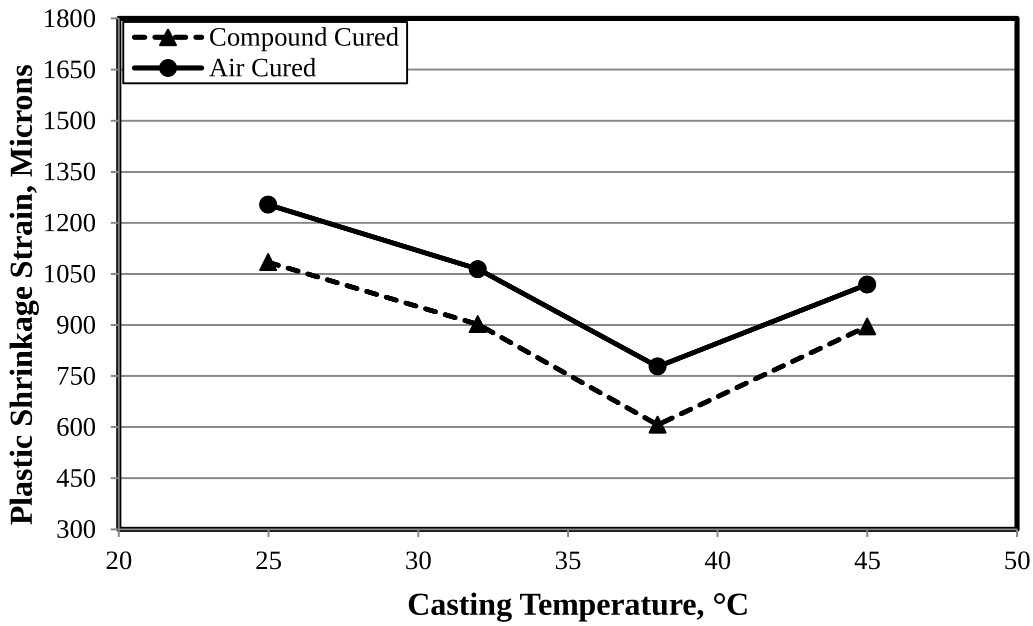

Figure 4.104: Maximum Plastic Shrinkage Strain in NP Cement Concretes.

4.5.7 Comparison of Plastic Shrinkage Strain in Cementitious Materials

Figures 4.105 and 4.106 depict the maximum plastic shrinkage strain in plain and blended cement concrete specimens prepared with a constant w/cm ratio of 0.4, cast at 25 to 45°C and subjected to air curing or application of a curing compound. The highest plastic shrinkage strain was noted in all concrete specimens cast at 25°C. However, a further increase in the temperature decreased the plastic shrinkage strain.

Among all cementitious materials, it was noted that irrespective of the curing regime utilized, the largest value of maximum plastic shrinkage strain occurred in the VFFA cement concrete specimens cast at 25 or 45°C, while the largest value of shrinkage strain was observed at 32°C in both the SF and FA cement concrete specimens. Similarly, the highest amount of maximum plastic shrinkage strain was noted in GGBFS cement concretes cast at 38°C. The minimum value of maximum plastic shrinkage strain was recorded at 25°C in both OPC and/or NP cement concretes while the minimum value of shrinkage strain was observed at 32°C in OPC concretes. However, when the specimens were cured by applying a curing compound (Fig. 4.105), the minimum value of maximum plastic shrinkage strain was recorded in FA cement concretes at both 38 and 45°C. Conversely, the minimum shrinkage strain at 38 and 45°C was noted in the NP and GGBFS cement concretes, respectively, when the specimens were cured in air.

The data in Table 4.18 shows the ratio of maximum value of plastic shrinkage strain in blended cement concretes compared to OPC concretes for a range of average of casting temperatures and curing regimes. The ratio of VFFA to OPC concretes was in the range of 0.86-1.31 (indicating that the maximum value of plastic shrinkage strain in VFFA cement concrete was about 14% lesser than OPC concrete at the casting temperature of

38°C, while it was 31% higher than OPC concrete at 32°C). The range of this ratio for FA, SF GGBFS and NP to OPC concrete was 0.83-1.65, 0.92-1.63, 0.81-148 and 0.81-1.32, respectively. The lowest ratio of maximum plastic shrinkage strain was noticed in both GGBFS and NP cement concretes which was comparable to the FA and VFFA cement concretes. However, the highest ratio of maximum plastic shrinkage strain was observed in FA cement concretes which was nearly equal to the SF cement concretes. Al-Gahtani [7] noted that the ratio of the maximum plastic shrinkage strain in VFFA, SF and FA cement concretes to OPC concrete specimens cured by covering with a plastic sheet or application of a water-based curing compound was on average 0.64, 0.45 and 0.77, respectively. Maslehuddin et al. [79] reported that such ratio of SF to OPC concrete was 1.43. Although Al-Amoudi et al. [46] observed a threshold value of plastic shrinkage strain of 1100 µm that could cause plastic shrinkage cracking in SF cement concrete, the results of this study exhibited plastic shrinkage strain of up to 1600 µm in some cementitious materials at certain temperatures. However, cracks were not observed on all concrete slabs prepared with plain or blended cement concretes which may be the consequence of the use of a good superplasticizer. The advantageous effect of superplasticizer on reducing the plastic shrinkage cracks was also reported by Al-Amoudi et al. [77] in another study, where plastic shrinkage strain of about 1250 µm was recorded in SF cement concrete without cracking. The addition of SF into OPC cement makes the concrete mix very cohesive thus there is meager bleeding which lead to plastic shrinkage cracking under drying conditions [32]. Increased plastic and drying shrinkage of SF cement concrete, especially under hot weather, has been reported by several authors [46,47].

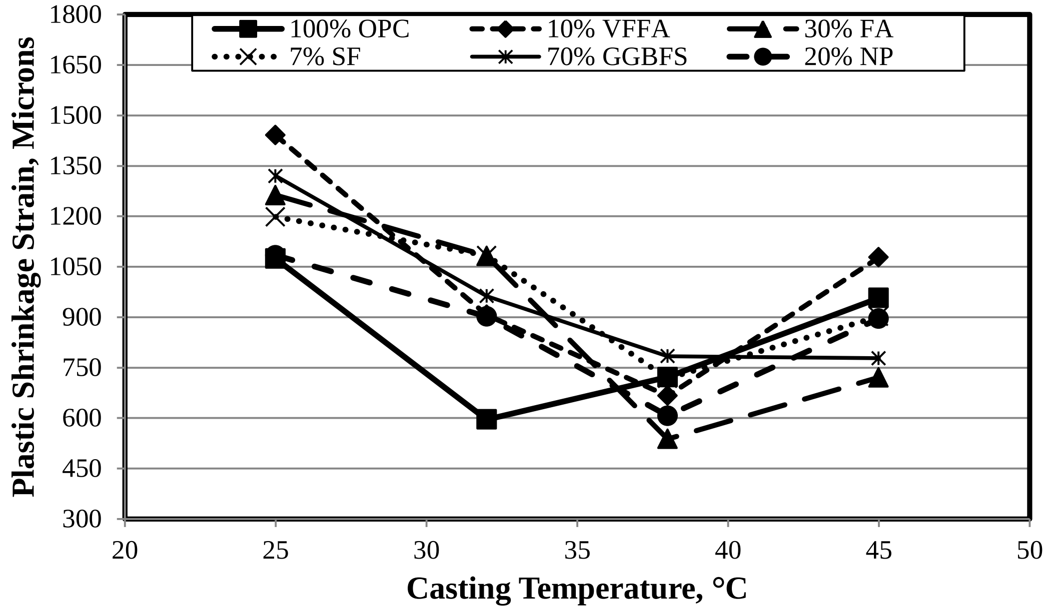

Figure 4.105: Maximum Plastic Shrinkage Strain in OPC and Blended Cement Concretes Prepared with w/cm Ratio of 0.4 and Cast at 25-45°C after Applying a Curing Compound.

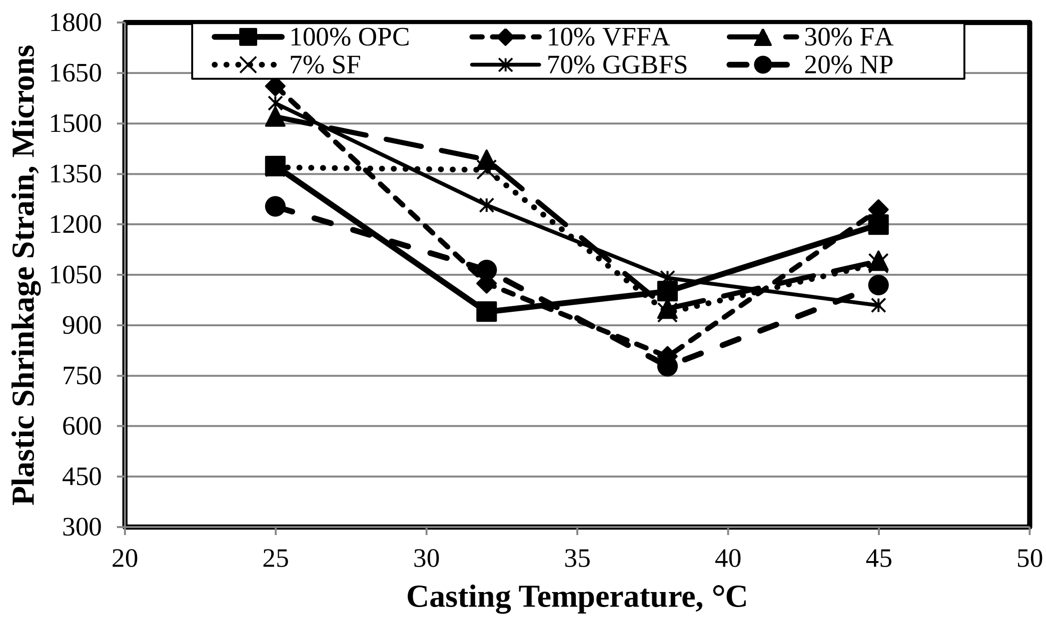

Figure 4.106: Maximum Plastic Shrinkage Strain in OPC and Blended Cement Concretes Prepared with w/cm Ratio of 0.4 and Cast at 25-45°C after Air Curing.

4.6 Drying Shrinkage Strain

The average drying shrinkage strain in OPC and blended cement concrete specimens, prepared with a w/cm ratio of 0.3, 0.4 or 0.45, cast at 25, 32, 38 or 45°C and tested after curing by covering with wet burlap or applying a curing compound is summarized in Tables 4.19 and 4.20. Moreover, quantitative analysis of the drying shrinkage strain of all types of concretes was carried out as shown in Table 4.21, where the drying shrinkage strain in each cementitious materials is expressed as a fraction of corresponding shrinkage strain in OPC concrete.

Table 4.19: Drying Shrinkage Strain in OPC and Blended Cement Concretes Cured by Covering with Wet Burlap.

Mix No.	Cementitious Materials	w/c ratio	Casting Temp. (°C)	Drying Shrinkage Strain (microns)						
				3 Days	10 Days	38 Days	73 Days	101 Days	129 Days	185 Days
1	100% OPC	0.3	25	103	221	273	361	419	450	471
2	100% OPC	0.3	32	12	163	202	260	309	342	351
3	100% OPC	0.3	38	40	179	212	322	382	410	420
4	100% OPC	0.3	45	51	171	231	311	390	432	451
5	100% OPC	0.4	25	231	380	422	523	593	630	661
6	100% OPC	0.4	32	2	184	231	292	331	361	380
7	100% OPC	0.4	38	181	309	342	402	493	530	563
8	100% OPC	0.4	45	231	340	392	501	592	641	671
9	100% OPC	0.45	25	212	402	463	554	630	672	700
10	100% OPC	0.45	32	12	170	200	279	342	391	412
11	100% OPC	0.45	38	200	319	359	501	568	617	638
12	100% OPC	0.45	45	250	360	399	509	610	670	701
13	OPC + 10% VFFA	0.4	25	240	337	382	539	591	657	709
14	OPC + 10% VFFA	0.4	32	70	210	250	336	410	450	478
15	OPC + 10% VFFA	0.4	38	141	253	280	359	380	480	519
16	OPC + 10% VFFA	0.4	45	147	266	308	428	519	582	619
17	OPC + 30% FA	0.4	25	221	312	361	497	592	641	679
18	OPC + 30% FA	0.4	32	-49	110	140	240	301	338	359
19	OPC + 30% FA	0.4	38	98	217	252	336	420	476	511
20	OPC + 30% FA	0.4	45	68	179	228	289	401	473	520
21	OPC + 7% SF	0.4	25	128	251	281	398	463	502	530
22	OPC + 7% SF	0.4	32	70	220	250	348	418	460	479
23	OPC + 7% SF	0.4	38	91	250	290	369	420	453	467
24	OPC + 7% SF	0.4	45	129	290	350	441	490	532	581
25	OPC + 70% GGBFS	0.4	25	266	361	389	508	620	681	732
26	OPC + 70% GGBFS	0.4	32	120	231	261	343	480	532	557
27	OPC + 70% GGBFS	0.4	38	180	271	310	469	518	591	630
28	OPC + 70% GGBFS	0.4	45	169	287	332	439	532	600	640
29	OPC + 20% NP	0.4	25	112	217	250	352	373	459	490
30	OPC + 20% NP	0.4	32	40	210	250	331	376	411	429
31	OPC + 20% NP	0.4	38	58	208	238	308	367	378	437
32	OPC + 20% NP	0.4	45	108	237	290	419	450	502	541

Table 4.20: Drying Shrinkage Strain in OPC and Blended Cement Concretes Cured by Applying a Curing Compound.

Mix No.	Cementitious Materials	w/c ratio	Casting Temp. (°C)	Drying Shrinkage Strain (microns)						
				3 Days	10 Days	38 Days	73 Days	101 Days	129 Days	185 Days
1	100% OPC	0.3	25	-10	31	90	118	170	201	212
2	100% OPC	0.3	32	-49	21	42	89	112	119	121
3	100% OPC	0.3	38	-28	33	63	114	142	163	163
4	100% OPC	0.3	45	-28	12	51	133	170	201	201
5	100% OPC	0.4	25	21	84	121	211	272	311	332
6	100% OPC	0.4	32	-51	0	21	60	102	132	132
7	100% OPC	0.4	38	0	40	72	142	203	219	219
8	100% OPC	0.4	45	-10	63	112	241	283	304	311
9	100% OPC	0.45	25	82	133	161	292	334	359	392
10	100% OPC	0.45	32	-30	12	33	91	140	161	170
11	100% OPC	0.45	38	37	61	110	142	208	238	252
12	100% OPC	0.45	45	19	132	170	263	318	360	372
13	OPC + 10% VFFA	0.4	25	98	168	231	266	326	385	409
14	OPC + 10% VFFA	0.4	32	-30	19	49	119	159	179	179
15	OPC + 10% VFFA	0.4	38	-9	49	82	131	164	180	192
16	OPC + 10% VFFA	0.4	45	-9	91	119	191	238	271	280
17	OPC + 30% FA	0.4	25	91	168	217	308	329	367	388
18	OPC + 30% FA	0.4	32	-51	9	40	79	110	119	121
19	OPC + 30% FA	0.4	38	0	80	119	140	171	189	199
20	OPC + 30% FA	0.4	45	-2	70	100	159	189	210	231
21	OPC + 7% SF	0.4	25	-21	28	63	129	182	210	227
22	OPC + 7% SF	0.4	32	-33	40	61	110	149	170	172
23	OPC + 7% SF	0.4	38	-2	68	89	119	149	177	191
24	OPC + 7% SF	0.4	45	-10	32	70	129	203	238	262
25	OPC + 70% GGBFS	0.4	25	140	182	199	301	381	430	460
26	OPC + 70% GGBFS	0.4	32	-9	42	61	128	149	210	231
27	OPC + 70% GGBFS	0.4	38	19	58	109	149	207	240	249
28	OPC + 70% GGBFS	0.4	45	-2	67	100	179	230	260	277
29	OPC + 20% NP	0.4	25	-19	28	51	122	166	199	208
30	OPC + 20% NP	0.4	32	-33	30	61	110	130	140	142
31	OPC + 20% NP	0.4	38	-28	52	77	108	143	167	174
32	OPC + 20% NP	0.4	45	-21	38	77	140	178	209	220

Table 4.21: Drying Shrinkage Strain in Blended Cement Concretes Compared to the Strain in OPC Concrete (0.4 w/c) - Average of all Curing Regimes.

Mix No.	Cementitious Materials	w/c Ratio	Casting Temp. (°C)	DS (Blended Cement) / DS (OPC) [6]
				185 Days
13	OPC + 10% VFFA	0.4	25	1.15
14	OPC + 10% VFFA	0.4	32	1.31
15	OPC + 10% VFFA	0.4	38	0.90
16	OPC + 10% VFFA	0.4	45	0.91
Range				**0.90 - 1.31**
17	OPC + 30% FA	0.4	25	1.10
18	OPC + 30% FA	0.4	32	0.93
19	OPC + 30% FA	0.4	38	0.91
20	OPC + 30% FA	0.4	45	0.76
Range				**0.76 - 1.10**
21	OPC + 7% SF	0.4	25	0.74
22	OPC + 7% SF	0.4	32	1.28
23	OPC + 7% SF	0.4	38	0.85
24	OPC + 7% SF	0.4	45	0.85
Range				**0.85 - 1.28**
25	OPC + 70% GGBFS	0.4	25	1.25
26	OPC + 70% GGBFS	0.4	32	1.61
27	OPC + 70% GGBFS	0.4	38	1.13
28	OPC + 70% GGBFS	0.4	45	0.92
Range				**0.92 - 1.61**
29	OPC + 20% NP	0.4	25	0.68
30	OPC + 20% NP	0.4	32	1.10
31	OPC + 20% NP	0.4	38	0.79
32	OPC + 20% NP	0.4	45	0.76
Range				**0.68 - 1.10**

[6] Ratio of drying shrinkage strain in blended cement concretes to plain cement concretes.

4.6.1 OPC Concrete

The drying shrinkage strain in OPC concrete (100% OPC) specimens prepared with w/c ratio of 0.3, 0.4 or 0.45, cast at 25, 32, 38 or 45°C and cured by covering with wet burlap or application of a curing compound is depicted in Figures 4.107 through 4.118. The drying shrinkage strain increased with age in all the concrete specimens. As expected, the increase was more rapid initially, stabilizing with time and remaining almost unchanged thereafter.

Effect of Curing Regime on Drying Shrinkage Strain in OPC Concrete

The drying shrinkage strain in the concrete specimens cured by applying a curing compound was less than that in the concrete specimens cured by covering with wet burlap. Regardless of any casting temperature and w/c ratio, the maximum drying shrinkage strain in the concrete specimens cured by applying a curing compound was on average 55.1% less than that in the concrete specimens cured by covering with wet burlap, as shown in Tables 4.19 and 4.20. The lower drying shrinkage strain in the concrete specimens cured by applying a curing compound is attributed to the greater resistance to water evaporation compared to that in the specimens cured by covering with wet burlap due to the protective film formed on the surface of concrete by the curing compound. The duration of curing is not a significant factor influencing the shrinkage and, therefore, drying shrinkage is higher in well-cured concrete [125].

Effect of Casting Temperature on Drying Shrinkage Strain in OPC Concrete

It could be noted that irrespective of w/c ratio and curing regime, the least value of maximum drying shrinkage strain at the age of 185 days was recorded in the concrete specimens cast at 32°C, followed by those that were cast at 38°C while specimens cast at

25 or 45°C resulted in almost similar and highest shrinkage values, as shown in Tables 4.19 and 4.20 and depicted in Figures 4.119 and 4.120. On average, the maximum drying shrinkage strain in the concrete specimens cast at 32°C was 43.4, 30.6 and 42.1% less than that in the concrete specimens cast at 25, 38 or 45°C, respectively. A higher shrinkage and cracking tendency at lower concrete temperature is possibly due to the potential of concrete to contract and the difference between coefficient of thermal expansion and contraction of the mix constituents, when concrete is placed in hot weather [32].

Effect of w/c Ratio on Drying Shrinkage Strain in OPC Concrete

As expected, the drying shrinkage strain in the OPC concrete specimens with similar casting temperature and curing method increased with an increase in the w/c ratio. On average, the maximum drying shrinkage strain in the concrete specimens prepared with w/c ratio of 0.3 was 26.9 and 34.3% less than that in the concrete specimens prepared with w/c ratio of 0.4 or 0.45, respectively, as shown in Tables 4.19 and 4.20. Further, the drying shrinkage strain in the concrete specimens prepared with w/c ratio of 0.4 was on average 10.1% less than that in the concrete specimens prepared with w/c ratio of 0.45. The increase in the drying shrinkage strain with an increase in the w/c ratio is due to the excess water available for evaporation. Brooks [126] reported that shrinkage of hydrated cement paste has a direct relation with water to cement ratios within a range of 0.2 to 0.6 while at w/c ratio higher than 0.6, the extra water is evaporated upon drying without causing shrinkage. Bao-guo et al. [76] also observed that drying shrinkage in OPC, SF and FA cement mortars decreases with lowering the water to binder ratio ranging from 0.3 to 0.6 after 28 days of moist curing.

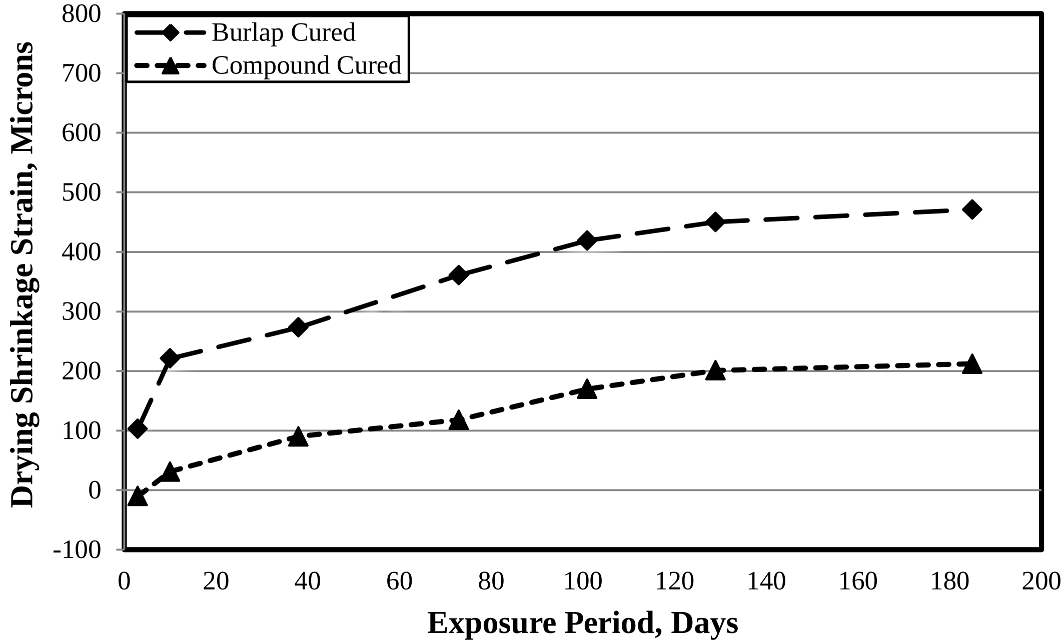

Figure 4.107: Drying Shrinkage Strain in OPC Concrete Prepared with w/c Ratio of 0.3 and Cast at 25°C.

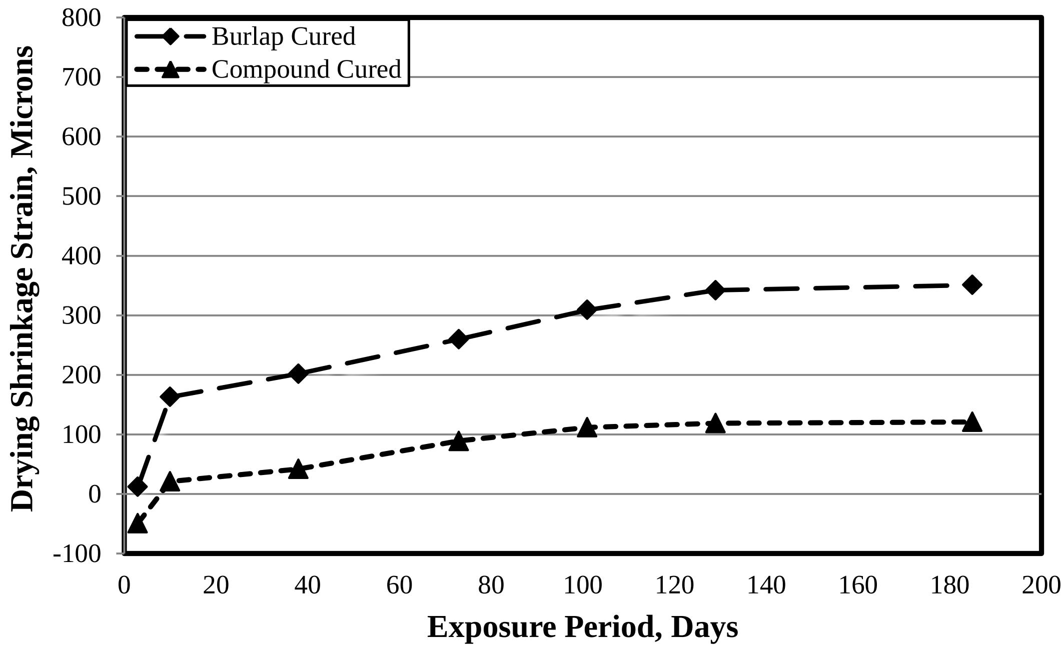

Figure 4.108: Drying Shrinkage Strain in OPC Concrete Prepared with w/c Ratio of 0.3 and Cast at 32°C.

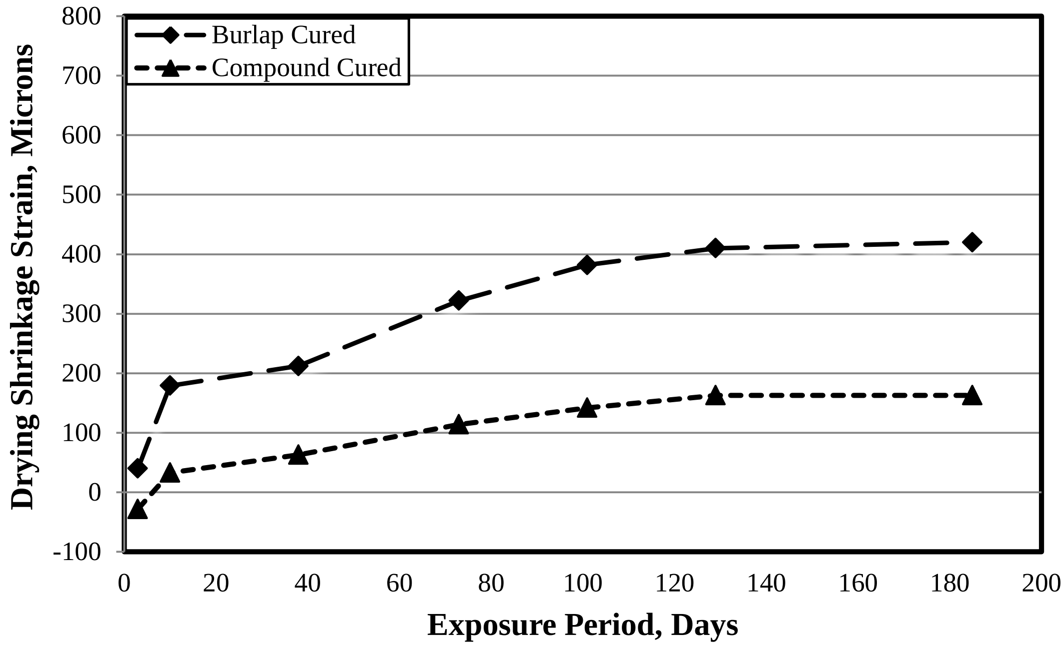

Figure 4.109: Drying Shrinkage Strain in OPC Concrete Prepared with w/c Ratio of 0.3 and Cast at 38°C.

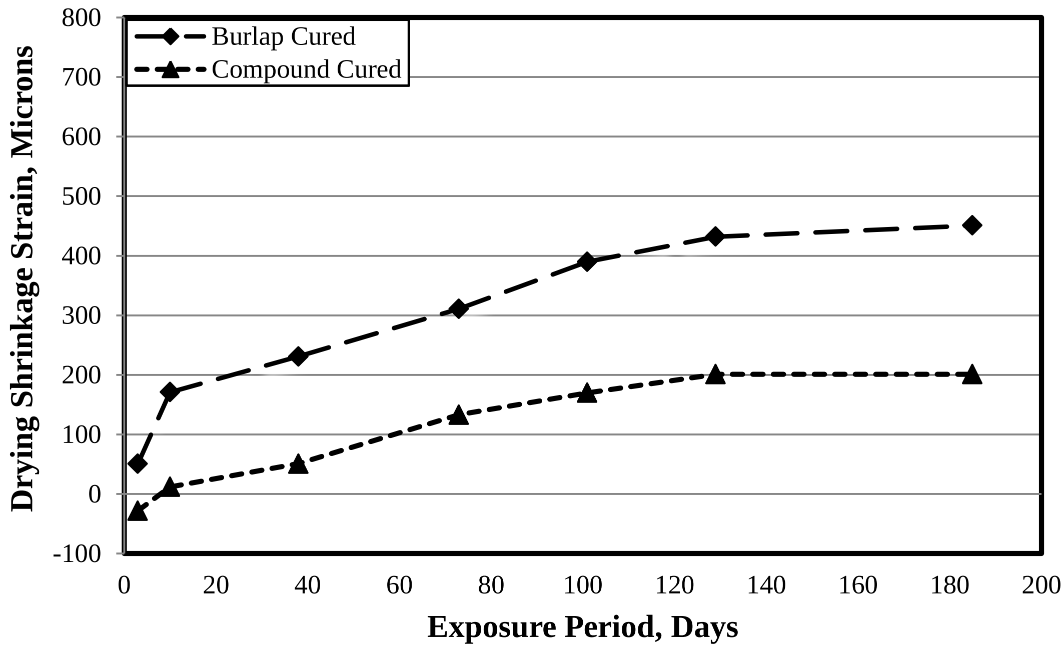

Figure 4.110: Drying Shrinkage Strain in OPC Concrete Prepared with w/c Ratio of 0.3 and Cast at 45°C.

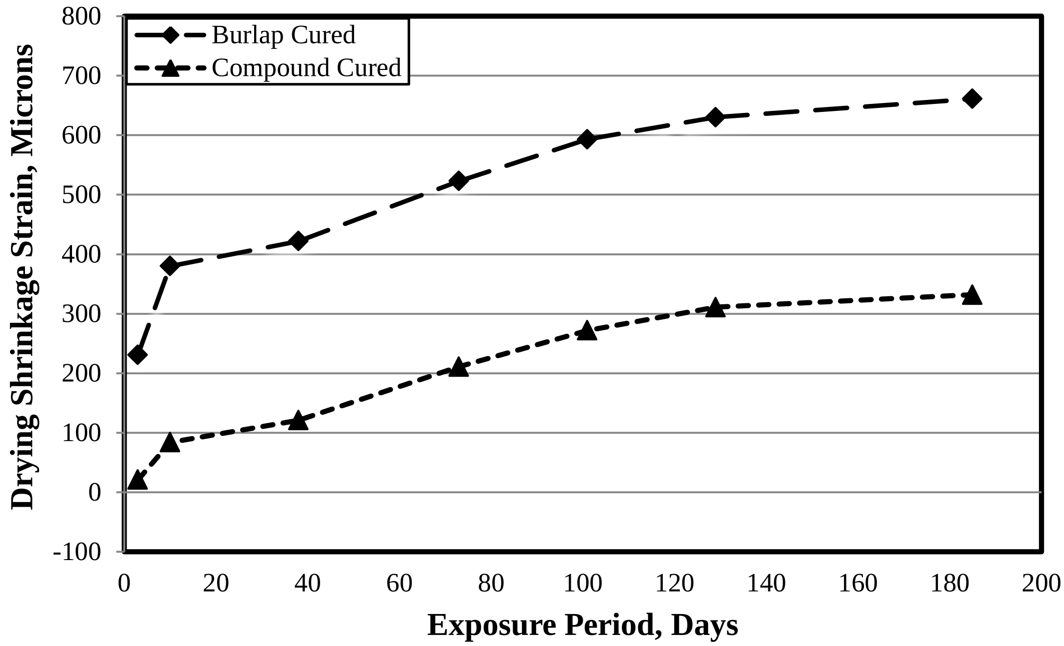

Figure 4.111: Drying Shrinkage Strain in OPC Concrete Prepared with w/c Ratio of 0.4 and Cast at 25°C.

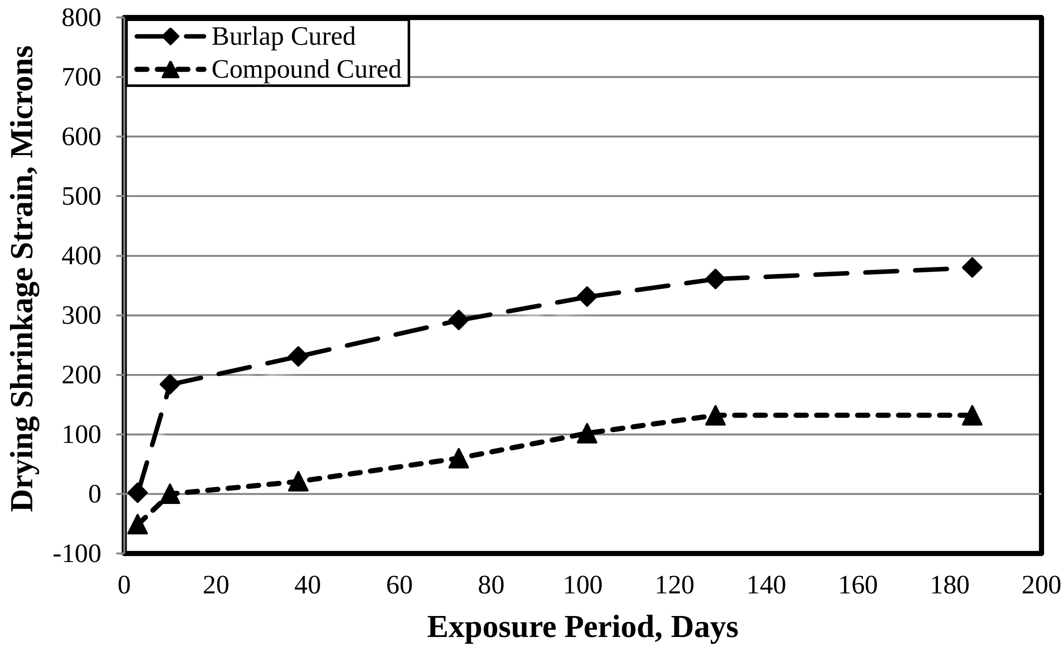

Figure 4.112: Drying Shrinkage Strain in OPC Concrete Prepared with w/c Ratio of 0.4 and Cast at 32°C.

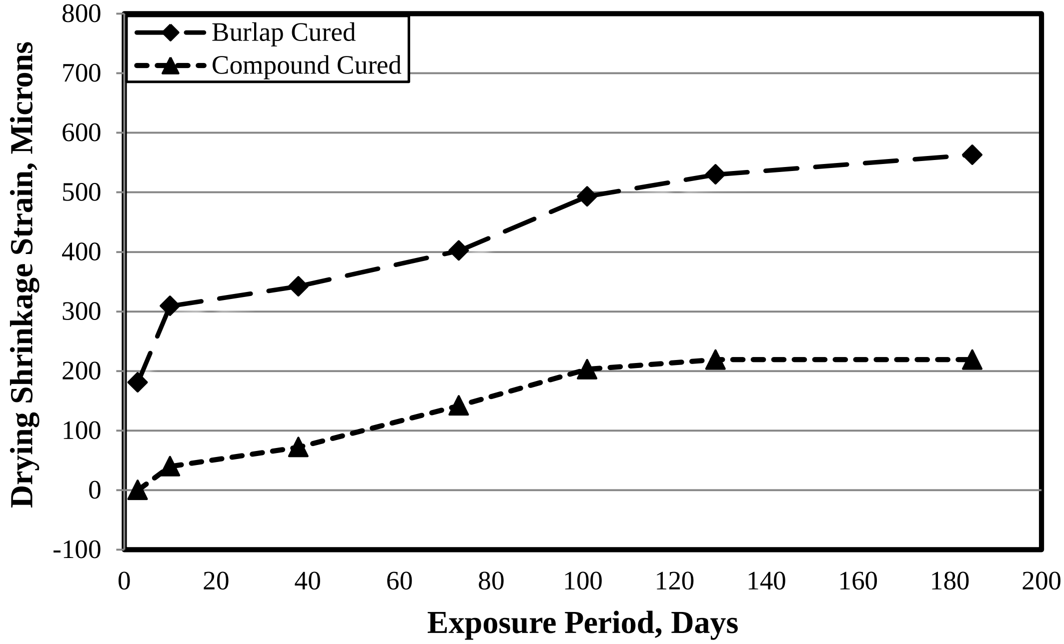

Figure 4.113: Drying Shrinkage Strain in OPC Concrete Prepared with w/c Ratio of 0.4 and Cast at 38°C.

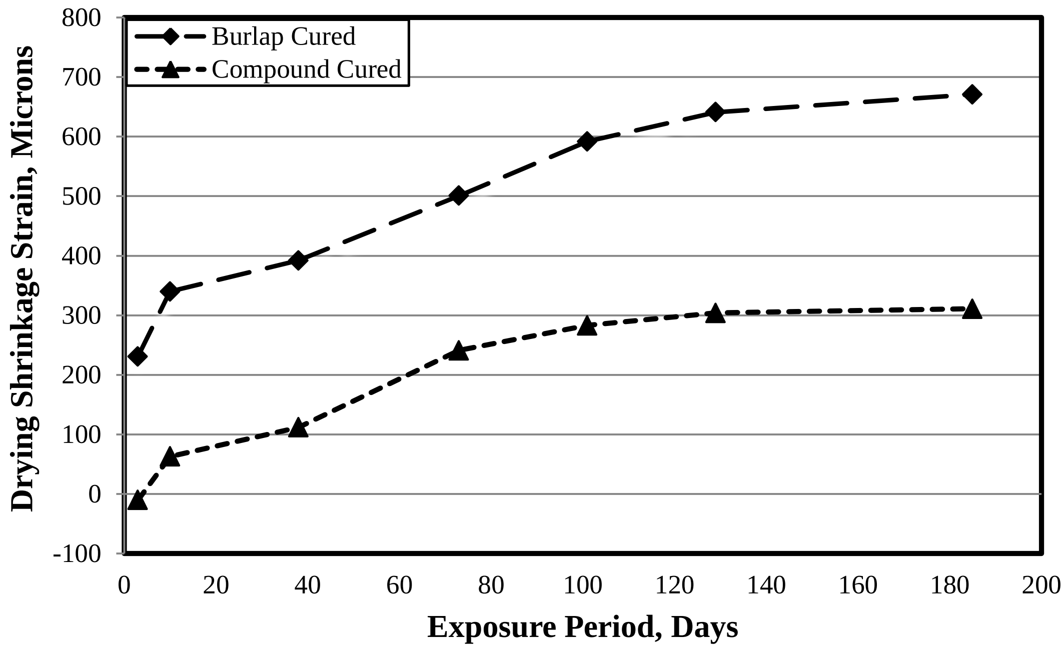

Figure 4.114: Drying Shrinkage Strain in OPC Concrete Prepared with w/c Ratio of 0.4 and Cast at 45°C.

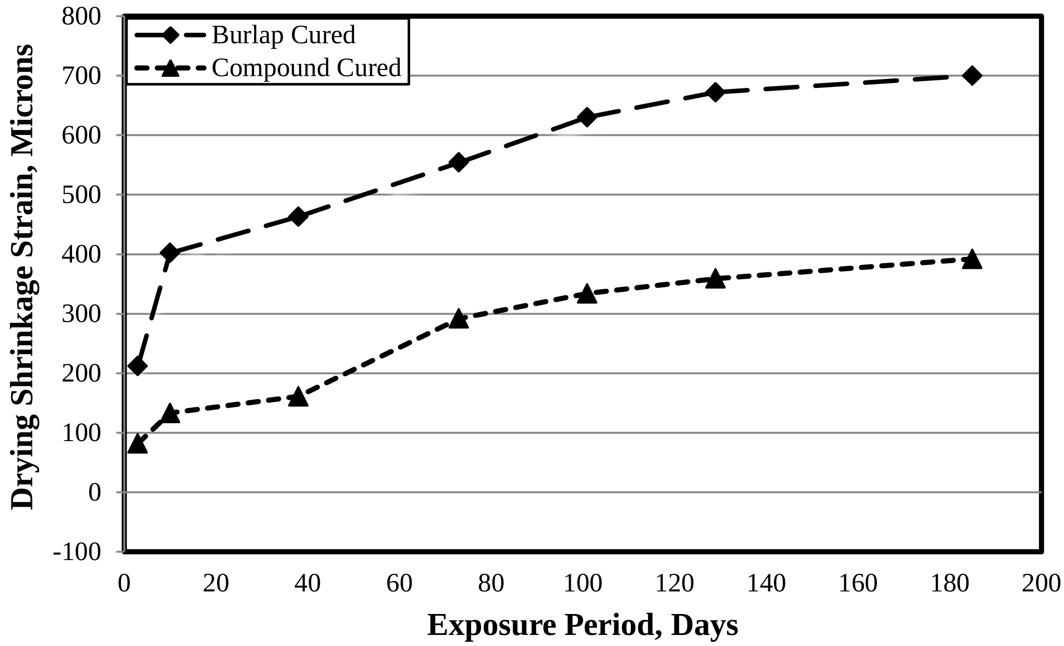

Figure 4.115: Drying Shrinkage Strain in OPC Concrete Prepared with w/c Ratio of 0.45 and Cast at 25°C.

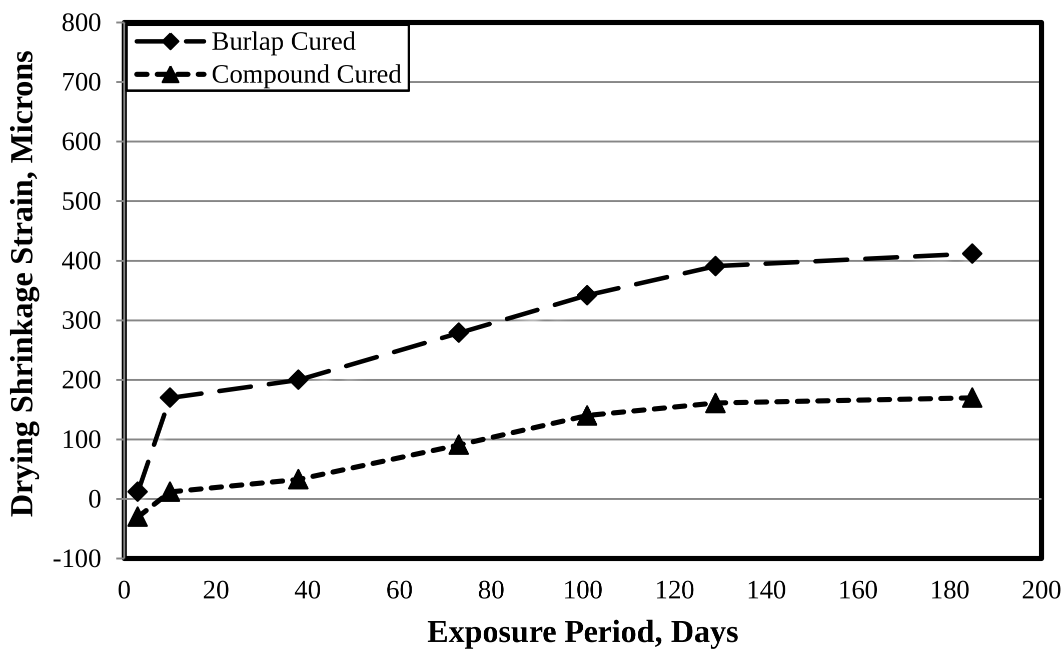

Figure 4.116: Drying Shrinkage Strain in OPC Concrete Prepared with w/c Ratio of 0.45 and Cast at 32°C.

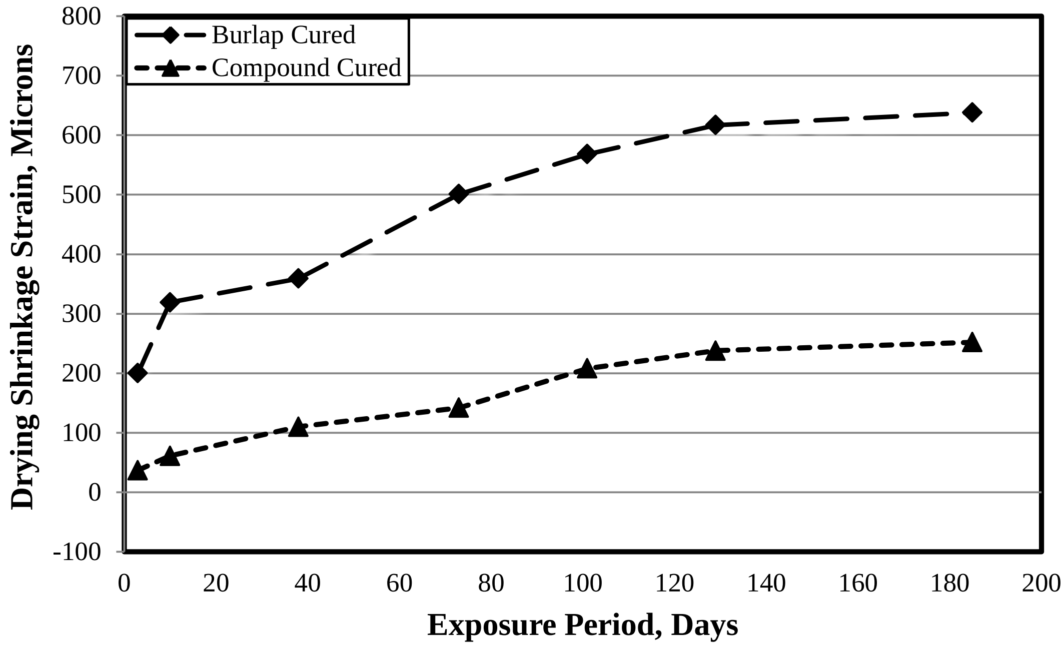

Figure 4.117: Drying Shrinkage Strain in OPC Concrete Prepared with w/c Ratio of 0.45 and Cast at 38°C.

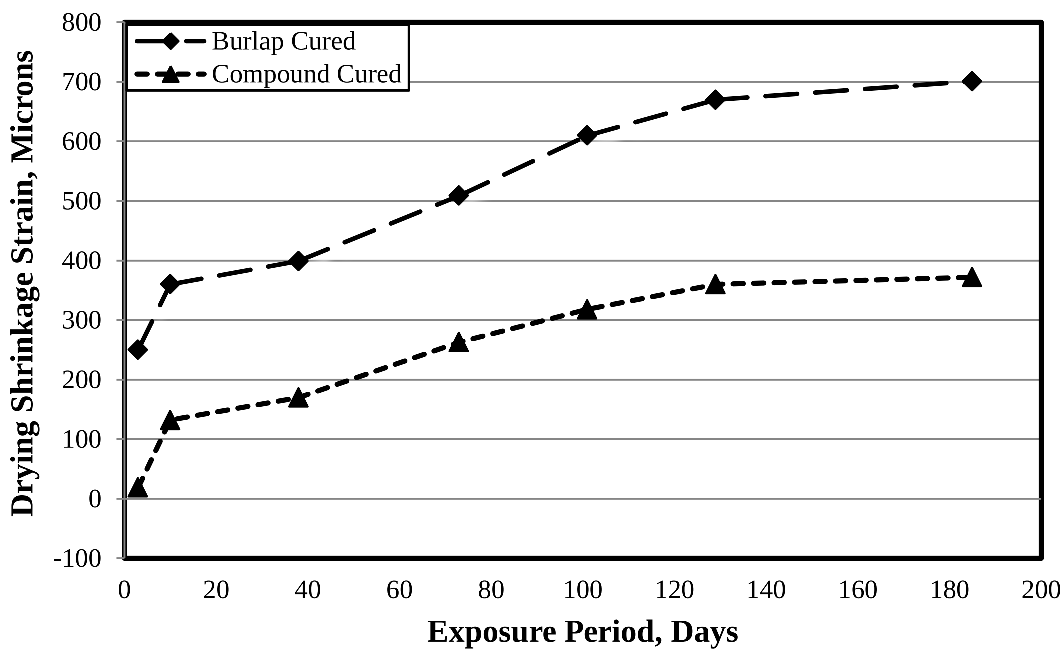

Figure 4.118: Drying Shrinkage Strain in OPC Concrete Prepared with w/c Ratio of 0.45 and Cast at 45°C.

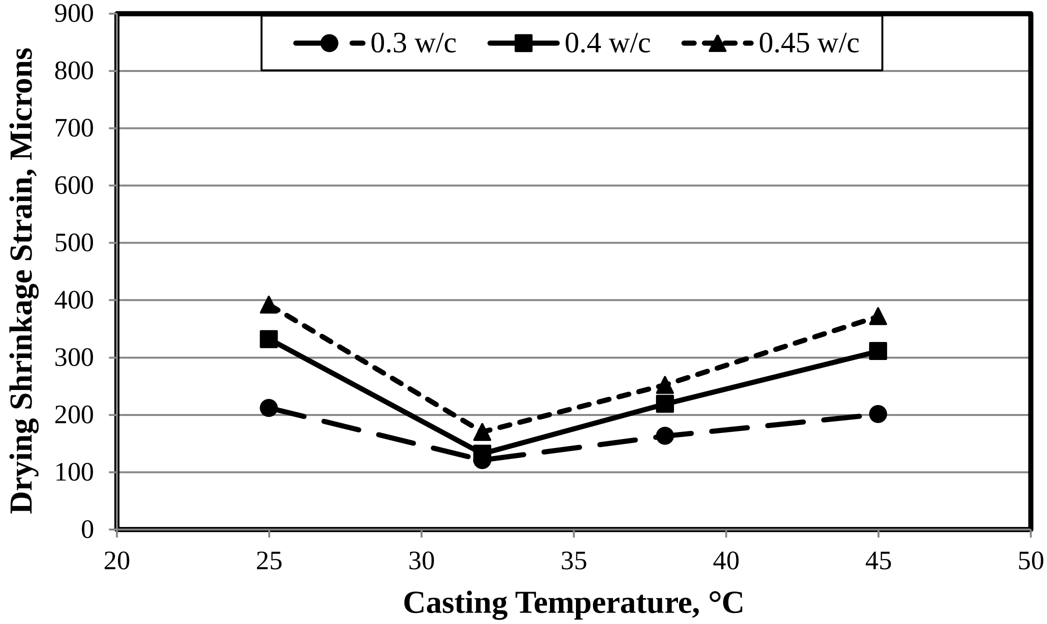

Figure 4.119: Maximum Drying Shrinkage Strain in OPC Concretes Prepared with w/c Ratio of 0.3-0.45 and Cast at 25-45°C after Applying a Curing Compound.

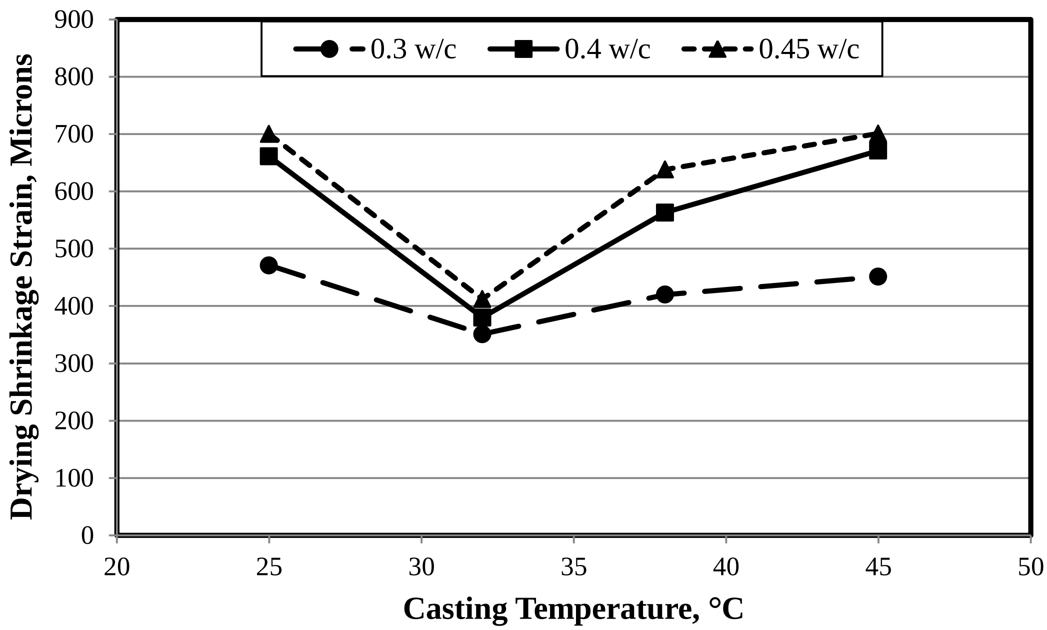

Figure 4.120: Maximum Drying Shrinkage Strain in OPC Concretes Prepared with w/c Ratio of 0.3-0.45 and Cast at 25-45°C after Curing by Covering with Wet Burlap.

4.6.2 VFFA Cement Concrete

The effect of partial replacement of OPC by 10% VFFA cement on the drying shrinkage strain is discussed in this section. For each curing regime, the relationships between the drying shrinkage strain and exposure period were plotted for all the concrete specimens prepared at a constant w/cm ratio of 0.4 and cast at varying temperatures of 25 to 45°C, as shown in Figures 4.121 through 4.124.

Effect of Curing Regime on Drying Shrinkage Strain in VFFA Cement Concrete

The drying shrinkage strain in the concrete specimens cured by applying a curing compound was less than that in the concrete specimens cured by covering with wet burlap. Despite any casting temperature investigated, the maximum drying shrinkage strain in the concrete specimens cured by application of a curing compound was on average 54.4% less than that in the concrete specimens cured by covering with wet burlap, as shown in Tables 4.19 and 4.20.

Effect of Casting Temperature on Drying Shrinkage Strain in VFFA Cement Concrete

Irrespective of the curing regime utilized, the least value of the maximum drying shrinkage strain was recorded in the concrete specimens cast at 32°C followed by those that were cast at 38 and 45°C, while the highest shrinkage strain was observed in the concrete specimens cast at 25°C, as shown in Tables 4.19 and 4.20 and depicted in Figure 4.125. On average, the maximum drying shrinkage strain in the concrete specimens cast at 32°C was 41.1, 7.6 and 28.9% less than that in the concrete specimens cast at 25, 38 or 45°C, respectively.

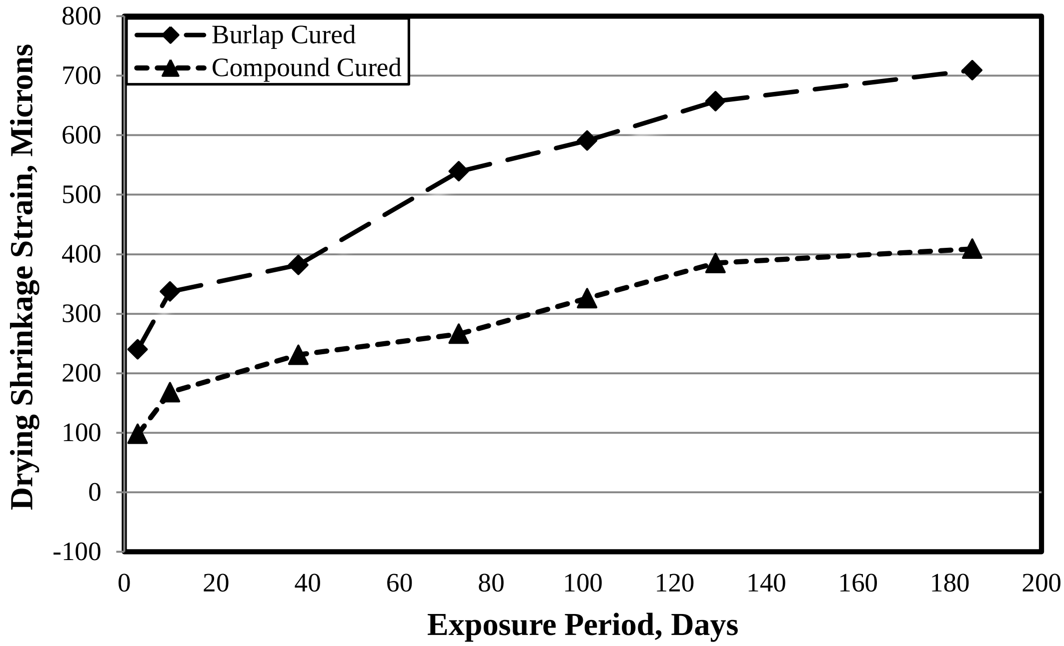

Figure 4.121: Drying Shrinkage Strain in VFFA Cement Concrete Prepared with w/cm Ratio of 0.4 and Cast at 25°C.

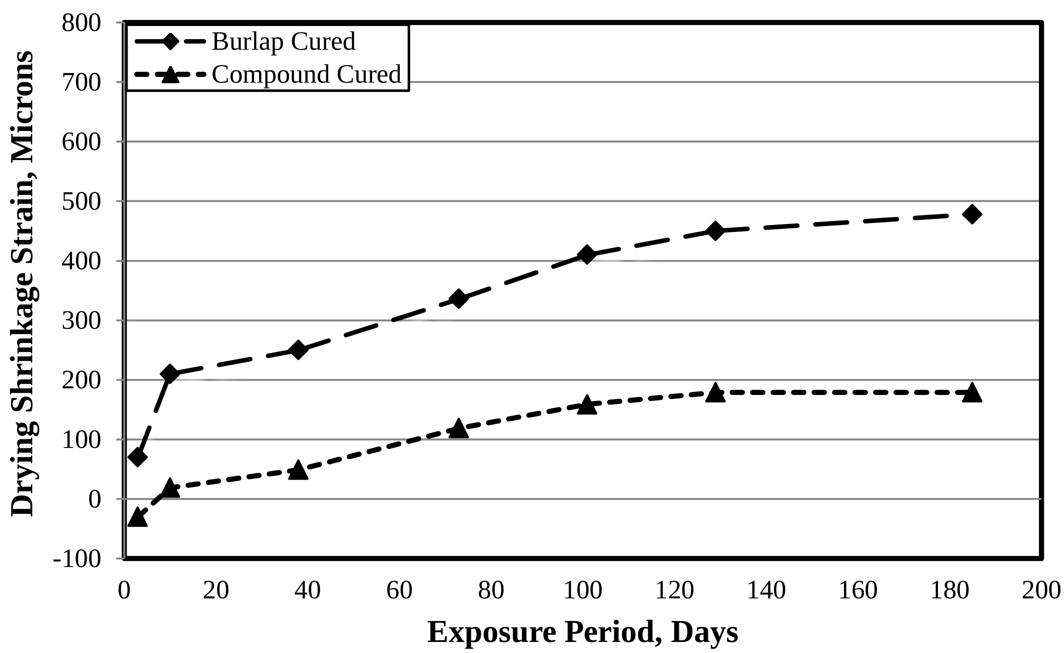

Figure 4.122: Drying Shrinkage Strain in VFFA Cement Concrete Prepared with w/cm Ratio of 0.4 and Cast at 32°C.

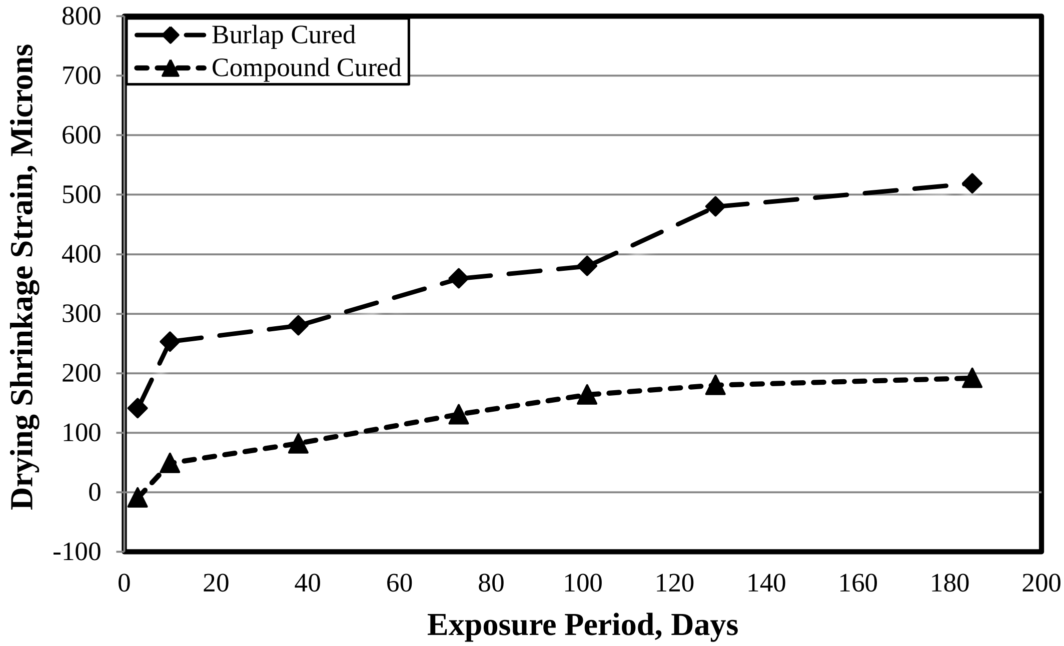

Figure 4.123: Drying Shrinkage Strain in VFFA Cement Concrete Prepared with w/cm Ratio of 0.4 and Cast at 38°C.

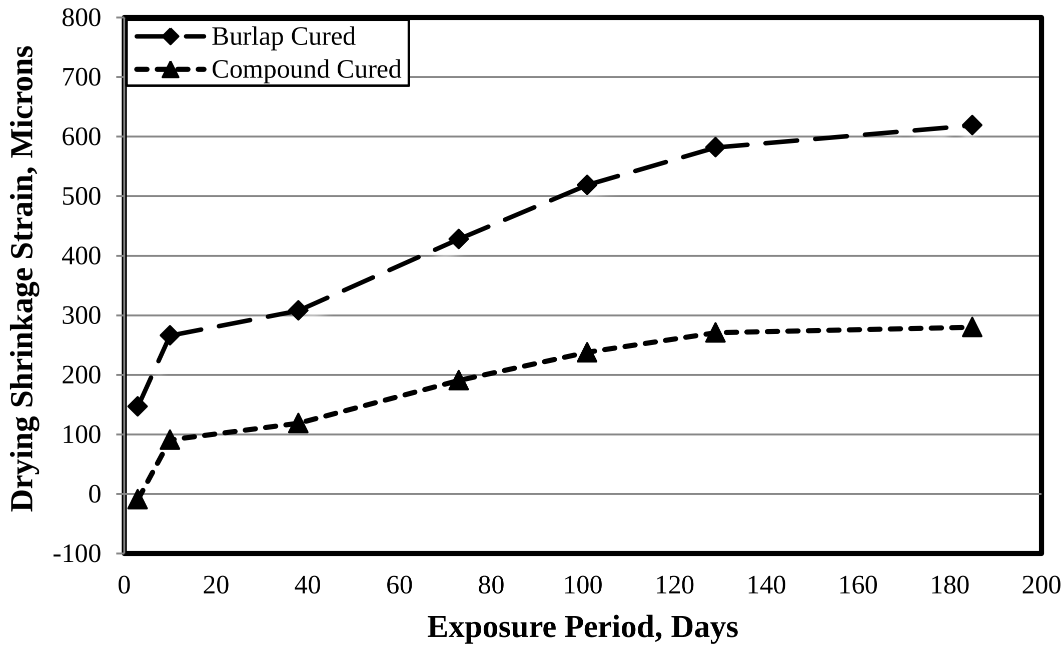

Figure 4.124: Drying Shrinkage Strain in VFFA Cement Concrete Prepared with w/cm Ratio of 0.4 and Cast at 45°C.

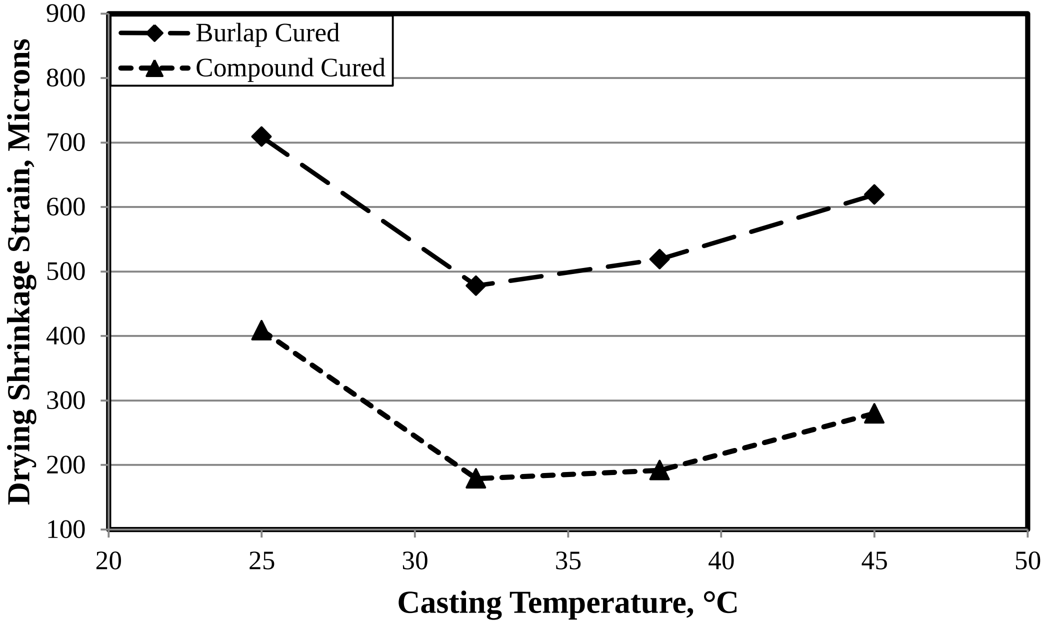

Figure 4.125: Maximum Drying Shrinkage Strain in VFFA Cement Concretes.

4.6.3 FA Cement Concrete

The drying shrinkage strain in FA cement concrete (OPC + 30% FA) specimens prepared with a w/cm ratio of 0.4, cast at 25, 32, 38 or 45°C and cured by covering with wet burlap or applying a curing compound is depicted in Figures 4.126 through 4.129.

Effect of Curing Regime on Drying Shrinkage Strain in FA Cement Concrete

From Tables 4.19 and 4.20, the drying shrinkage strain in the concrete specimens cured by applying a curing compound was on average 54.5% less than that in the concrete specimens cured by covering with wet burlap.

Effect of Casting Temperature on Drying Shrinkage Strain in FA Cement Concrete

Regardless of any curing regime, the least value of maximum drying shrinkage strain was recorded in the concrete specimens cast at 32°C followed by those that were cast at 38 and 45°C, while the highest shrinkage strain was measured in the concrete specimens cast at 25°C, as shown in Tables 4.19 and 4.20 and depicted in Figure 4.130. On average, the maximum drying shrinkage strain in the concrete specimens cast at 32°C was 55.0, 32.4 and 36.2% less than that in the concrete specimens cast at 25, 38 or 45°C, respectively.

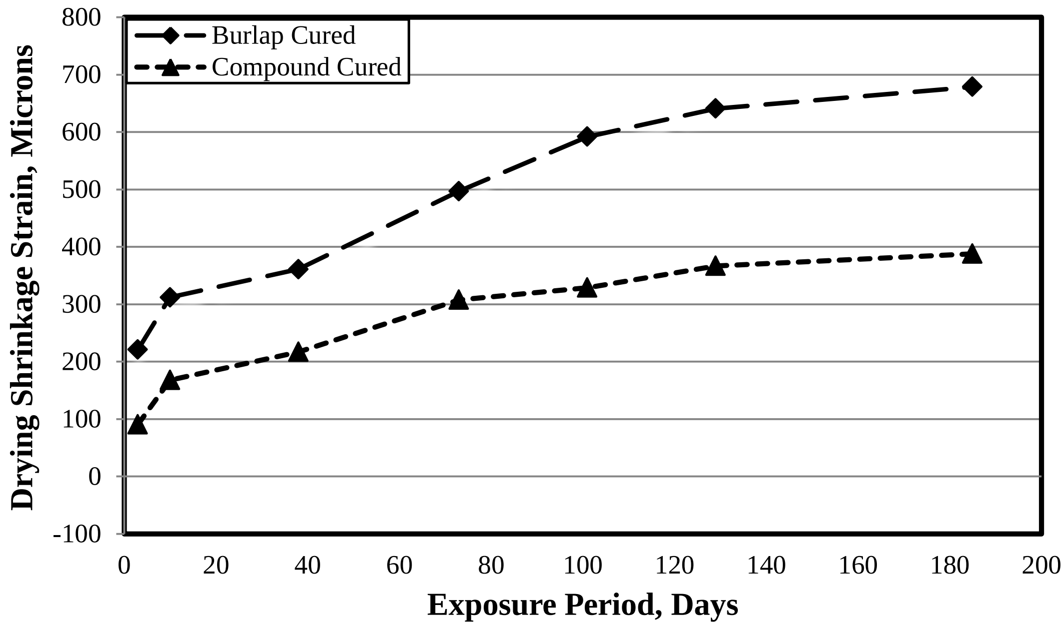

Figure 4.126: Drying Shrinkage Strain in FA Cement Concrete Prepared with w/cm Ratio of 0.4 and Cast at 25°C.

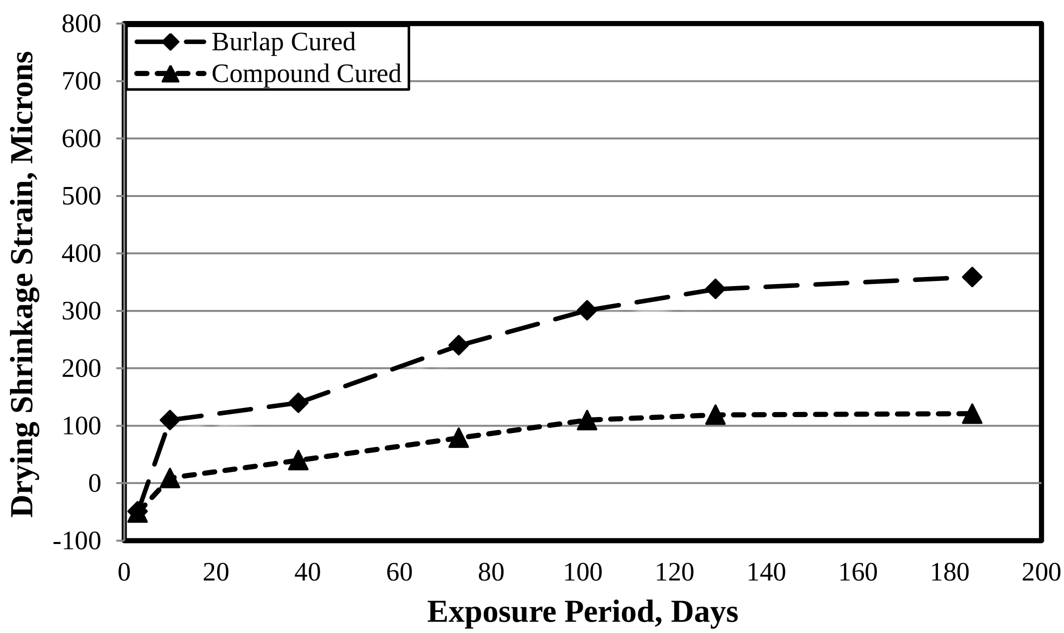

Figure 4.127: Drying Shrinkage Strain in FA Cement Concrete Prepared with w/cm Ratio of 0.4 and Cast at 32°C.

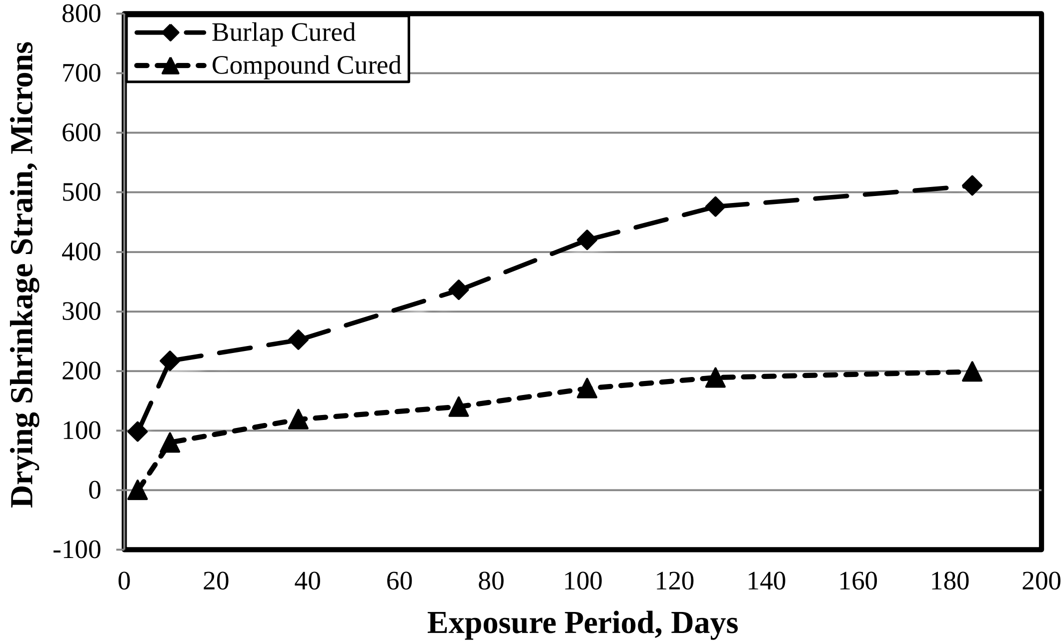

Figure 4.128: Drying Shrinkage Strain in FA Cement Concrete Prepared with w/cm Ratio of 0.4 and Cast at 38°C.

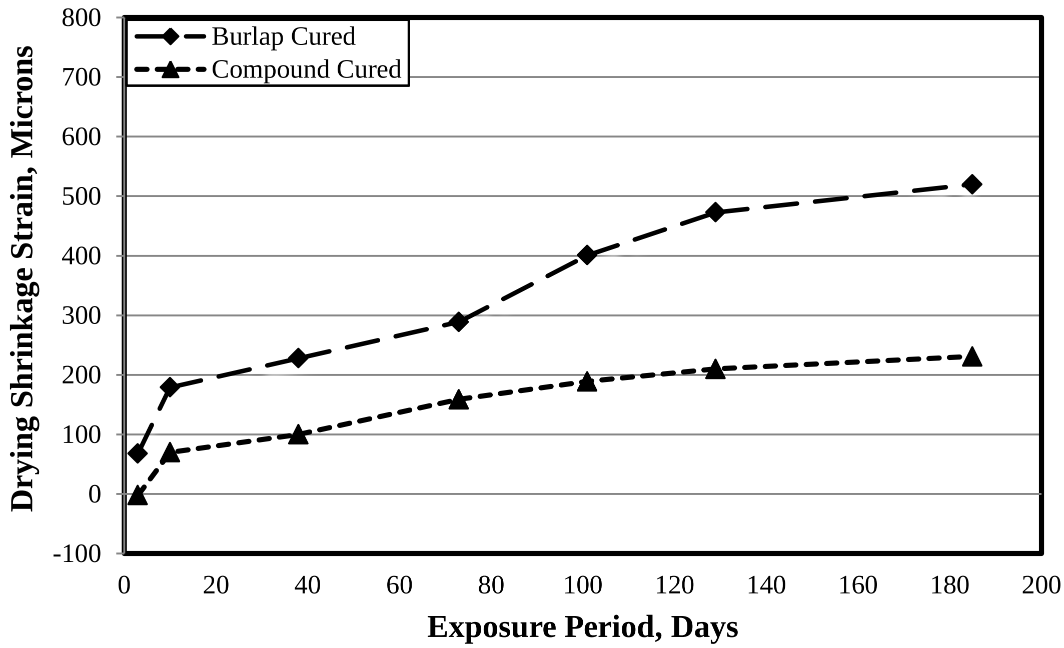

Figure 4.129: Drying Shrinkage Strain in FA Cement Concrete Prepared with w/cm Ratio of 0.4 and Cast at 45°C.

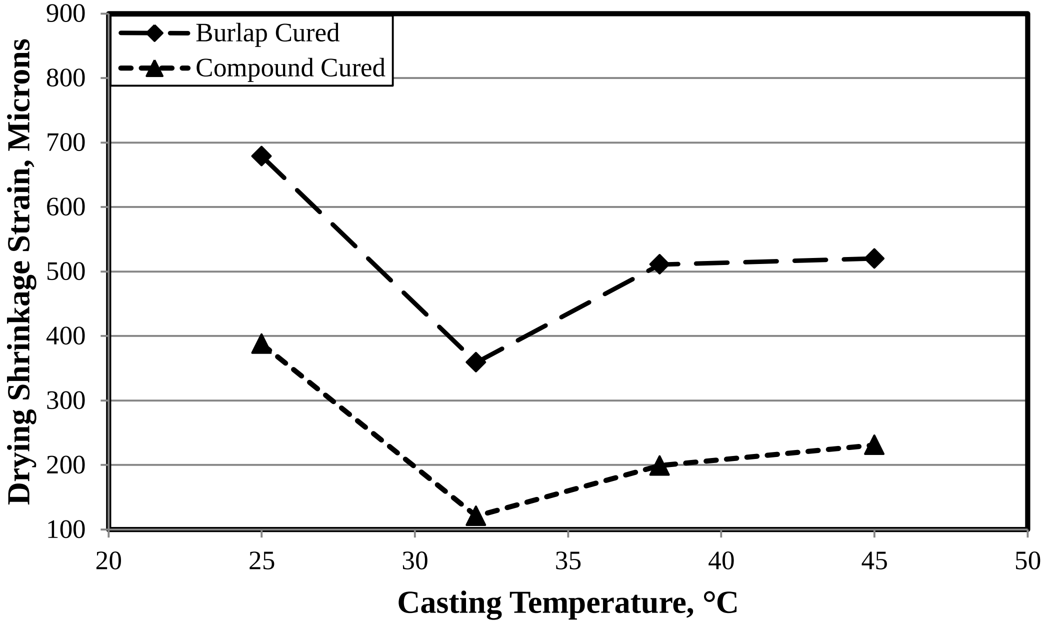

Figure 4.130: Maximum Drying Shrinkage Strain in FA Cement Concretes.

4.6.4 SF Cement Concrete

The drying shrinkage strain in SF cement concrete (OPC + 7% SF) specimens prepared with a constant w/cm ratio of 0.4, cast at range of temperatures of 25, 32, 38 or 45°C and cured by covering with wet burlap or application of a curing compound is depicted in Figures 4.131 through 4.134.

Effect of Curing Regime on Drying Shrinkage Strain in SF Cement Concrete

On average, the maximum drying shrinkage strain in the concrete specimens cured by applying a curing compound was 58.6% less than that in the concrete specimens cured by covering with wet burlap, as shown in Tables 4.19 and 4.20. Whitting et al. [80] noted that the cracking tendency and drying shrinkage in SF cement concrete was higher than OPC concrete, and, therefore, 7-days of moist curing to exposed concretes without interruption is essential.

Effect of Casting Temperature on Drying Shrinkage Strain in SF Cement Concrete

For all the curing regimes, the least value of maximum drying shrinkage strain was recorded in the concrete specimens cast at either 32 or 38°C, while the highest shrinkage strain was measured in the concrete specimens cast at either 25 or 45°C, as shown in Tables 4.19 and 4.20 and depicted in Figure 4.135. On average, the maximum drying shrinkage strain in the concrete specimens cast at 32°C was 14.0, 1.0 and 22.7% less than that in the concrete specimens cast at 25, 38 or 45°C, respectively.

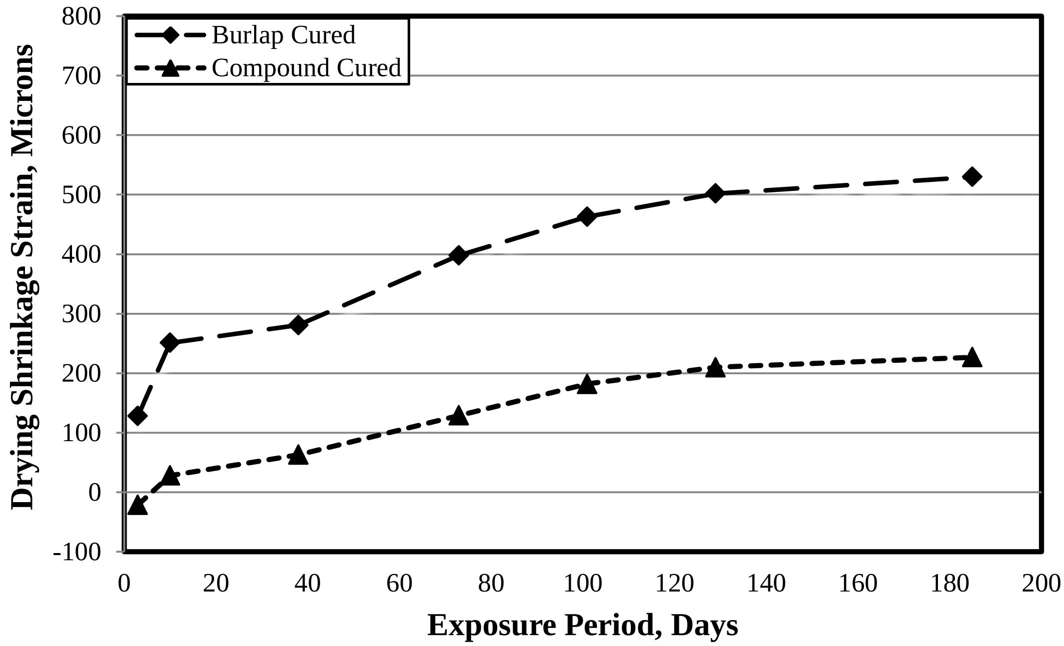

Figure 4.131: Drying Shrinkage Strain in SF Cement Concrete Prepared with w/cm Ratio of 0.4 and Cast at 25°C.

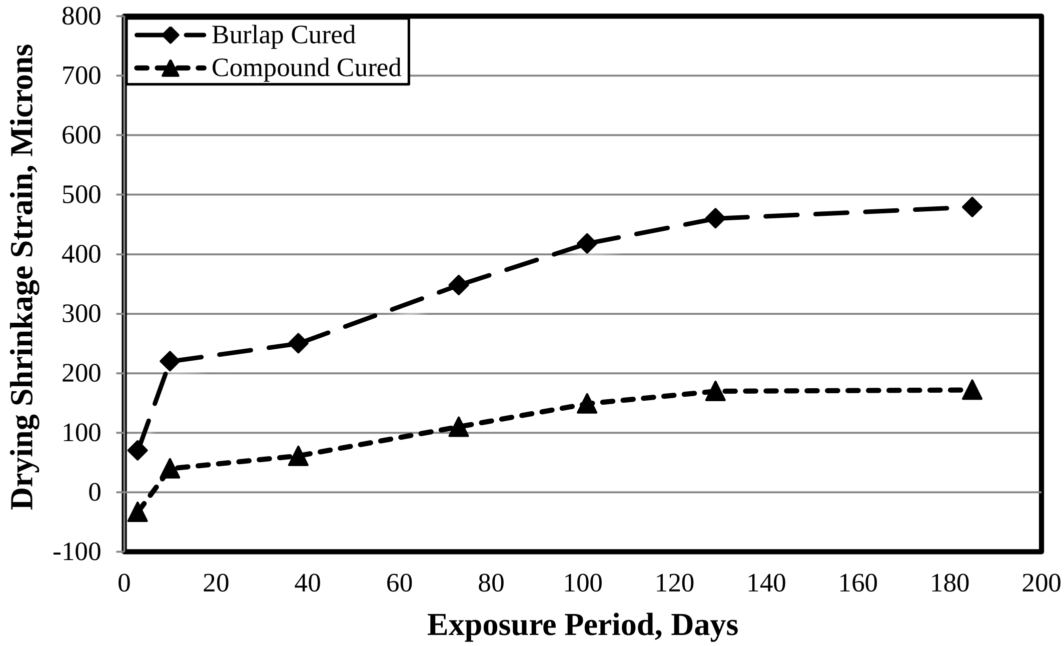

Figure 4.132: Drying Shrinkage Strain in SF Cement Concrete Prepared with w/cm Ratio of 0.4 and Cast at 32°C.

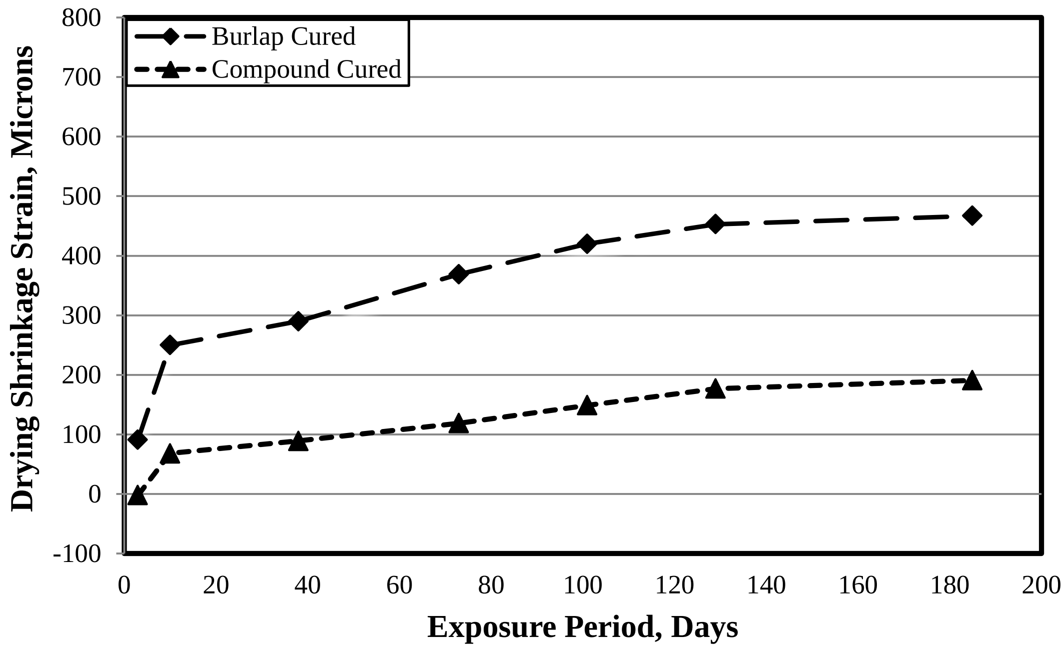

Figure 4.133: Drying Shrinkage Strain in SF Cement Concrete Prepared with w/cm Ratio of 0.4 and Cast at 38°C.

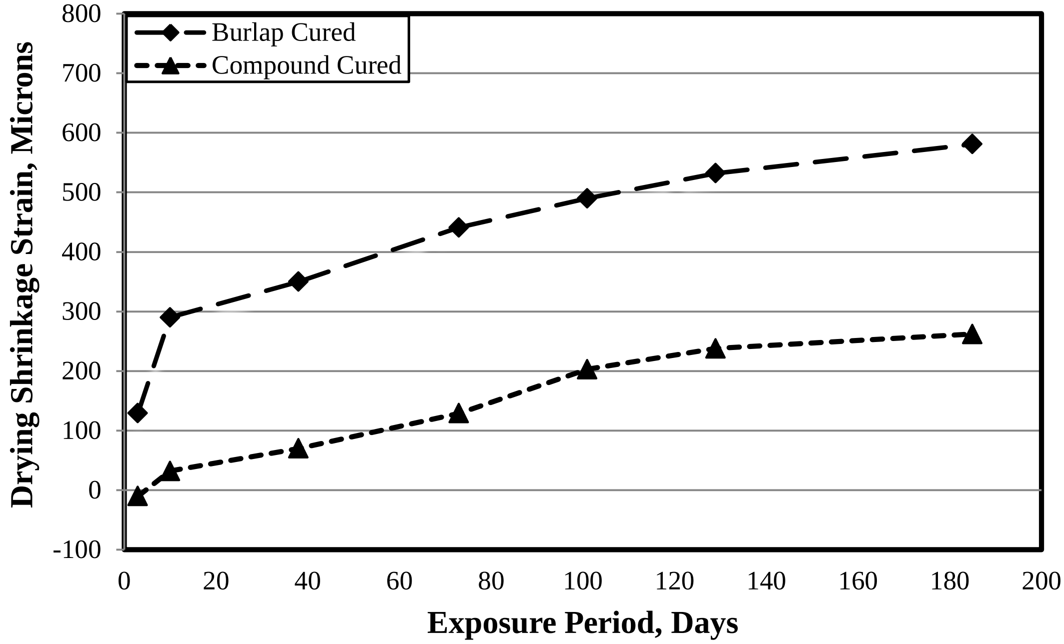

Figure 4.134: Drying Shrinkage Strain in SF Cement Concrete Prepared with w/cm Ratio of 0.4 and Cast at 45°C.

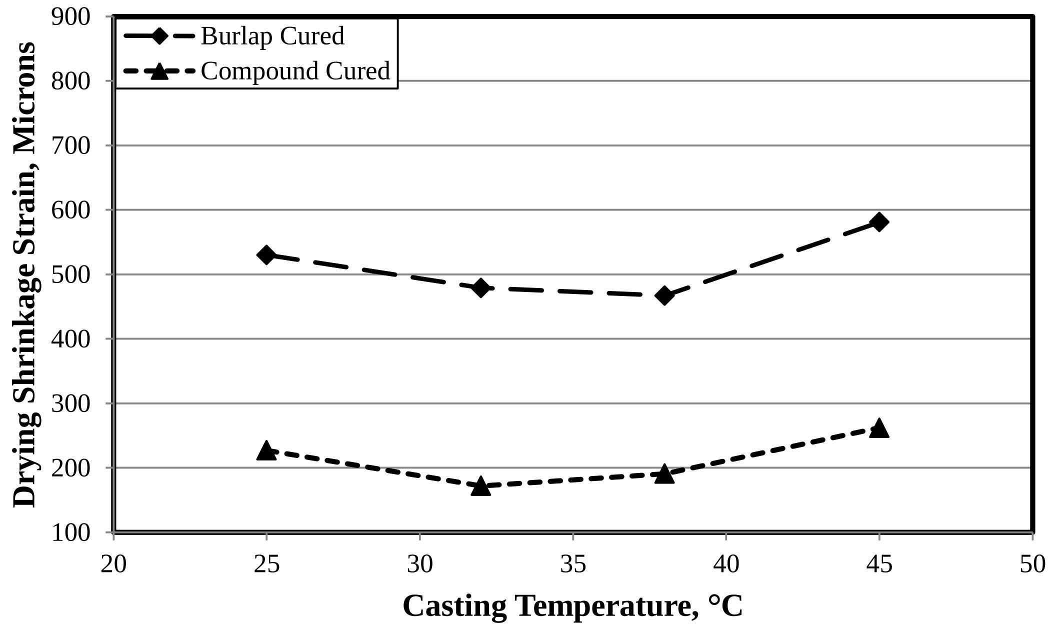

Figure 4.135: Maximum Drying Shrinkage Strain in SF Cement Concretes.

4.6.5 GGBFS Cement Concrete

The effect of partial replacement of OPC by 70% GGBFS on the drying shrinkage strain is discussed in this section. For each curing regime, the relationships between the drying shrinkage strain and exposure time were plotted for all the concrete specimens prepared at a w/cm ratio of 0.4 and cast at varying temperatures of 25 to 45°C, as shown in Figures 4.136 through 4.139.

Effect of Curing Regime on Drying Shrinkage Strain in GGBFS Cement Concrete

On average, the maximum drying shrinkage strain in the concrete specimens cured by applying a curing compound was 52.5% less than that in the concrete specimens cured by covering with wet burlap, as shown in Tables 4.19 and 4.20.

Effect of Casting Temperature on Drying Shrinkage Strain in GGBFS Cement Concrete

Despite of any curing regime used, the least value of maximum drying shrinkage strain was recorded in the concrete specimens cast at 32°C followed by those that were cast at either 38 or 45°C, while the highest shrinkage strain was observed in the concrete specimens cast at 25°C, as shown in Tables 4.19 and 4.20 and depicted in Figure 4.140. On average, the maximum drying shrinkage strain in the concrete specimens cast at 32°C was 33.9, 10.5 and 14.2% less than that in the concrete specimens cast at 25, 38 or 45°C, respectively.

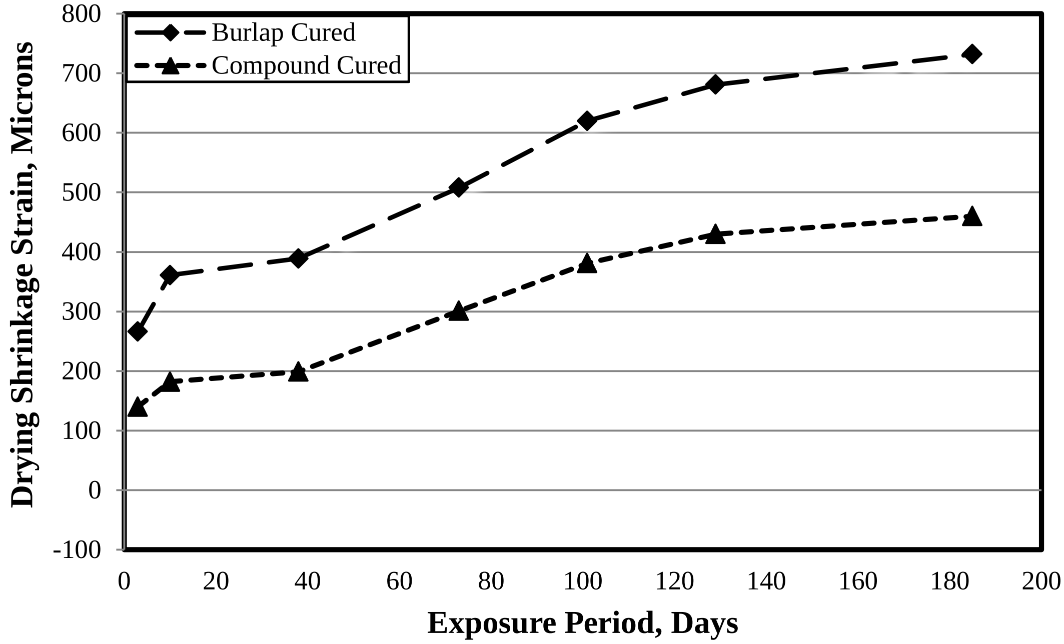

Figure 4.136: Drying Shrinkage Strain in GGBFS Cement Concrete Prepared with w/cm Ratio of 0.4 and Cast at 25°C.

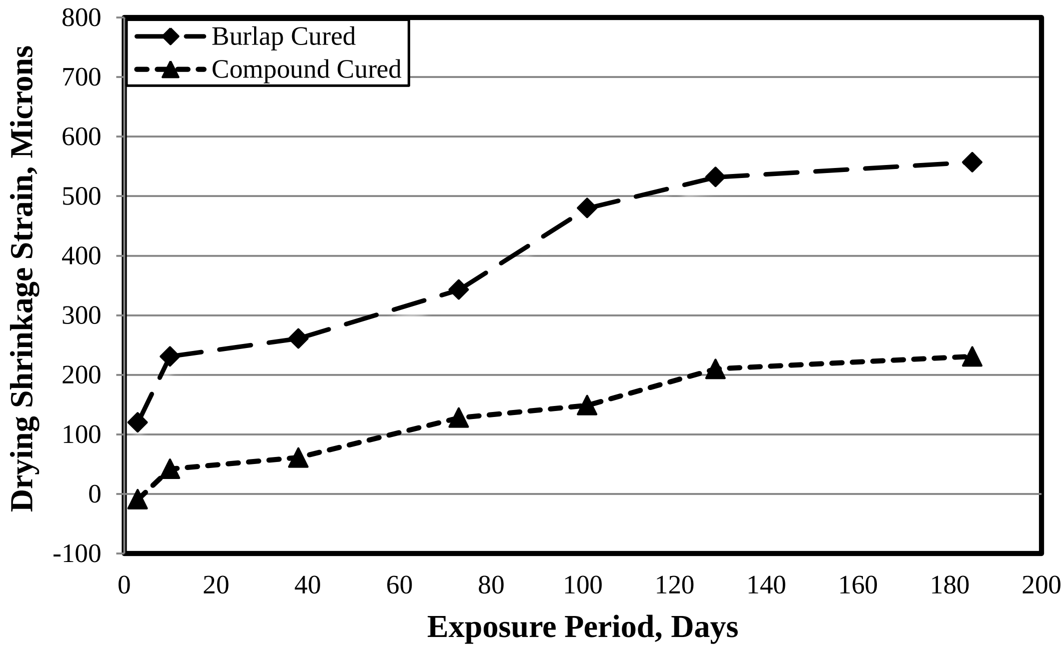

Figure 4.137: Drying Shrinkage Strain in GGBFS Cement Concrete Prepared with w/cm Ratio of 0.4 and Cast at 32°C.

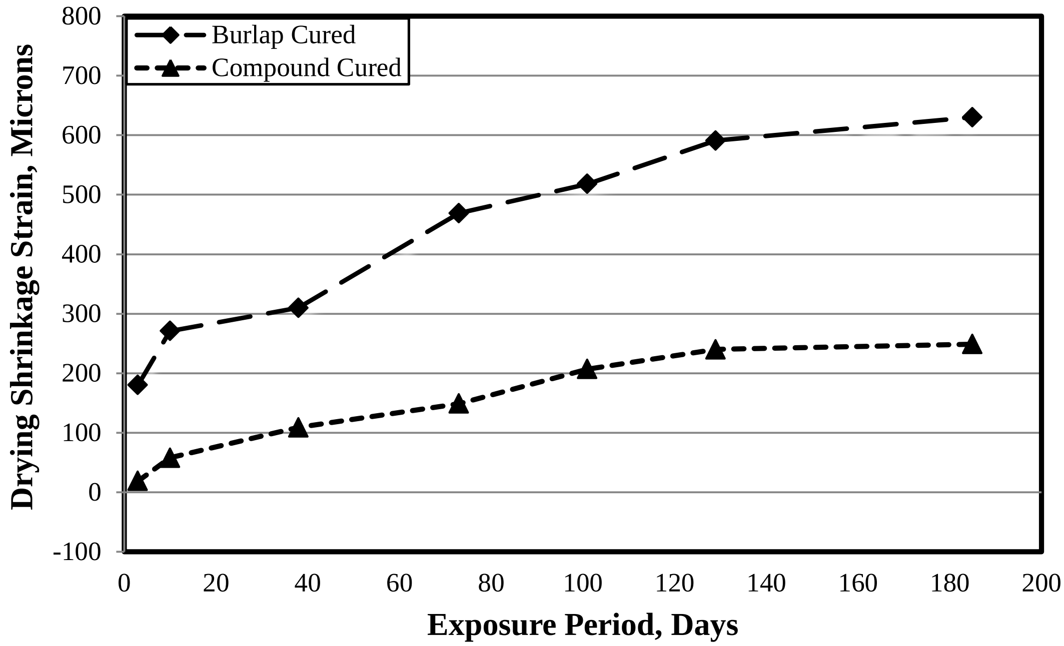

Figure 4.138: Drying Shrinkage Strain in GGBFS Cement Concrete Prepared with w/cm Ratio of 0.4 and Cast at 38°C.

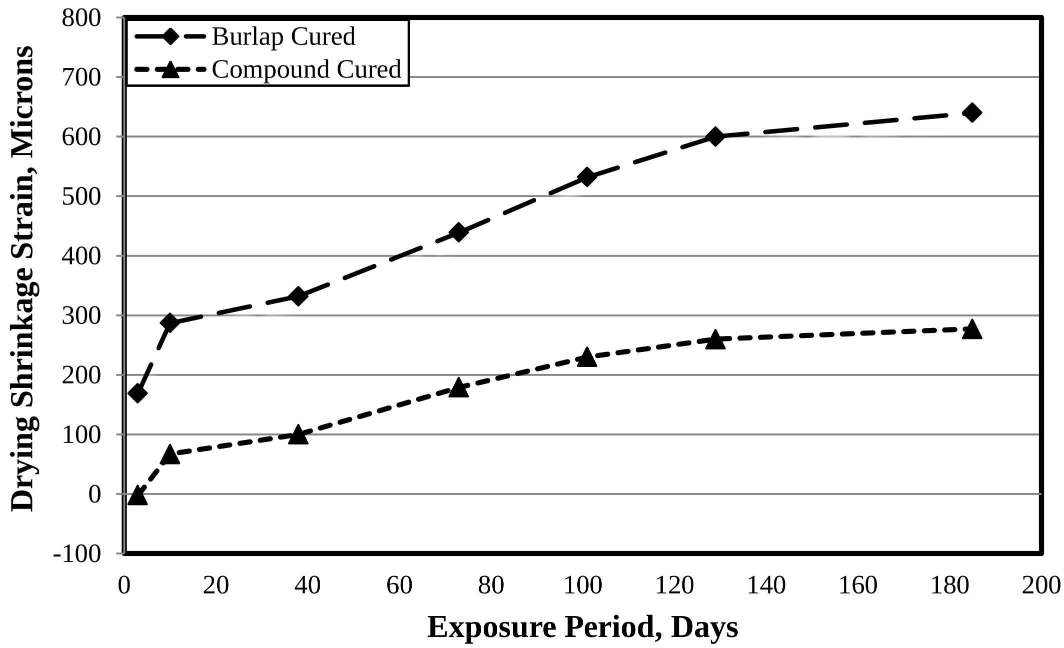

Figure 4.139: Drying Shrinkage Strain in GGBFS Cement Concrete Prepared with w/cm Ratio of 0.4 and Cast at 45°C.

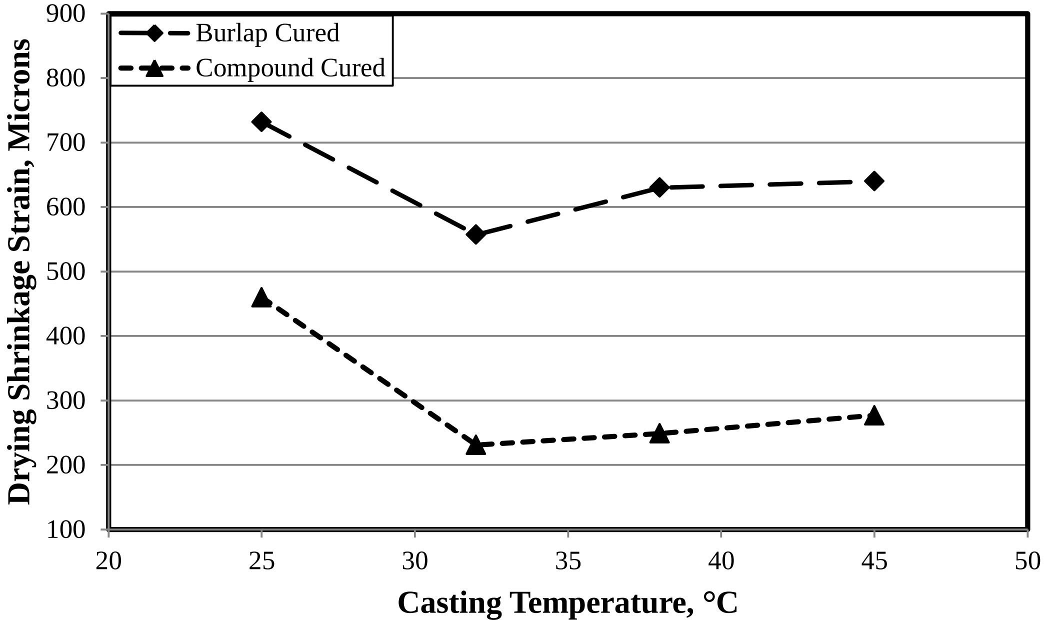

Figure 4.140: Maximum Drying Shrinkage Strain in GGBFS Cement Concretes.

4.6.6 NP Cement Concrete

The drying shrinkage strain in NP cement concrete (OPC + 20% NP) specimens prepared with a w/cm ratio of 0.4, cast at 25, 32, 38 or 45°C and cured by covering with wet burlap or applying a curing compound is depicted in Figures 4.141 through 4.144.

Effect of Curing Regime on Drying Shrinkage Strain in NP Cement Concrete

As shown in Tables 4.19 and 4.20, the drying shrinkage strain in the concrete specimens cured by application of a curing compound was on average 60.8% less than that in the concrete specimens cured by covering with wet burlap.

Effect of Casting Temperature on Drying Shrinkage Strain in NP Cement Concrete

Regardless of the curing regime, the least value of maximum drying shrinkage strain was measured in the concrete specimens cast at either 32 or 38°C, while the highest shrinkage strain was recorded in the concrete specimens cast at either 25 or 45°C, as shown in Tables 4.19 and 4.20 and depicted in Figure 4.145. On average, the maximum drying shrinkage strain in the concrete specimens cast at 32°C was 18.1, 6.5 and 24.9% less than that in the concrete specimens cast at 25, 38 or 45°C, respectively.

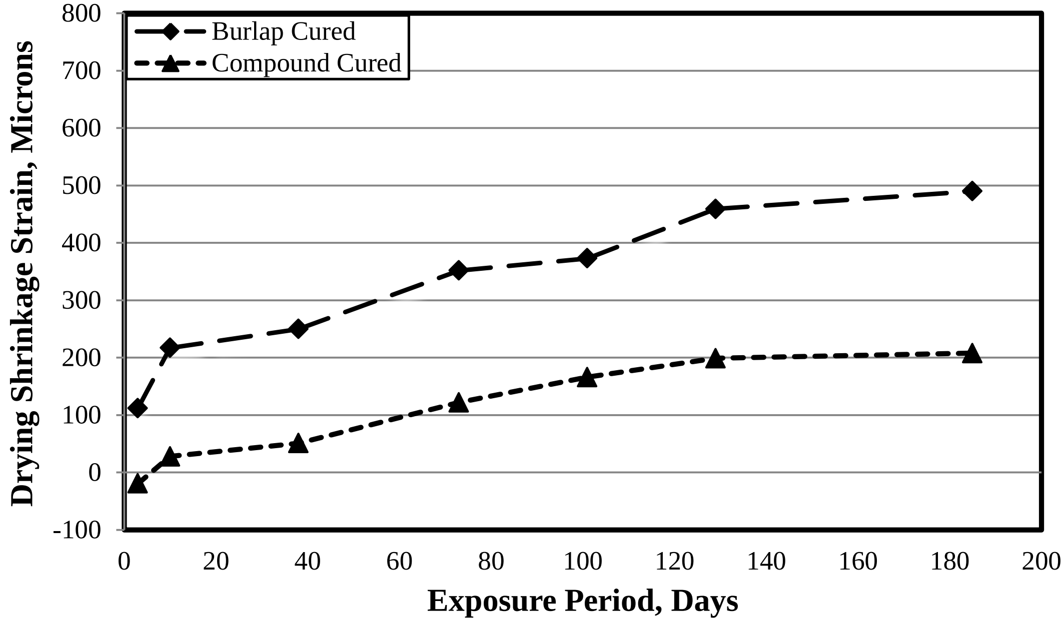

Figure 4.141: Drying Shrinkage Strain in NP Cement Concrete Prepared with w/cm Ratio of 0.4 and Cast at 25°C.

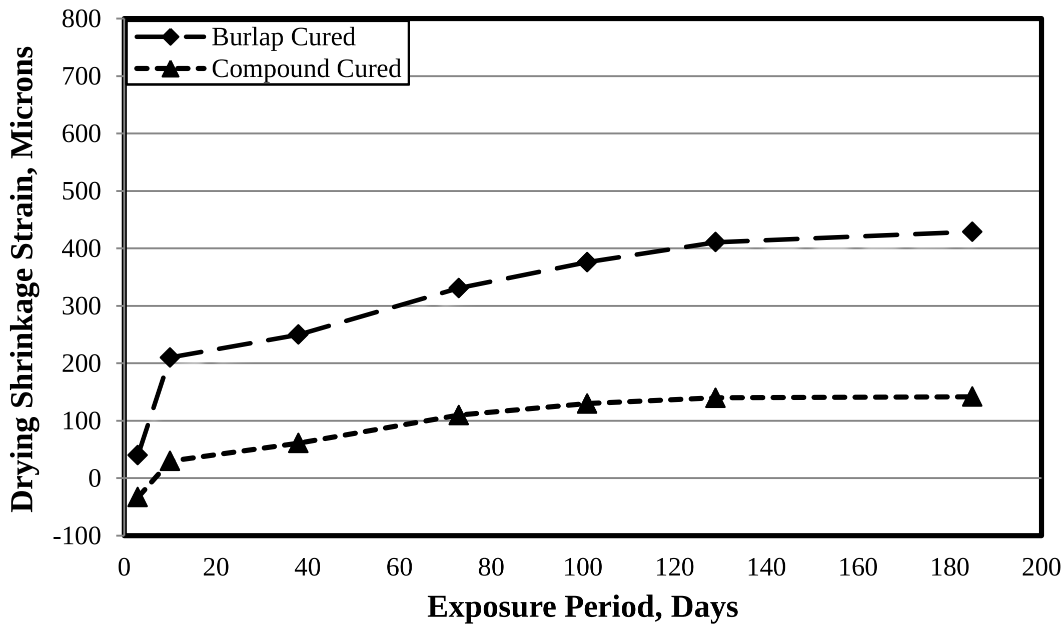

Figure 4.142: Drying Shrinkage Strain in NP Cement Concrete Prepared with w/cm Ratio of 0.4 and Cast at 32°C.

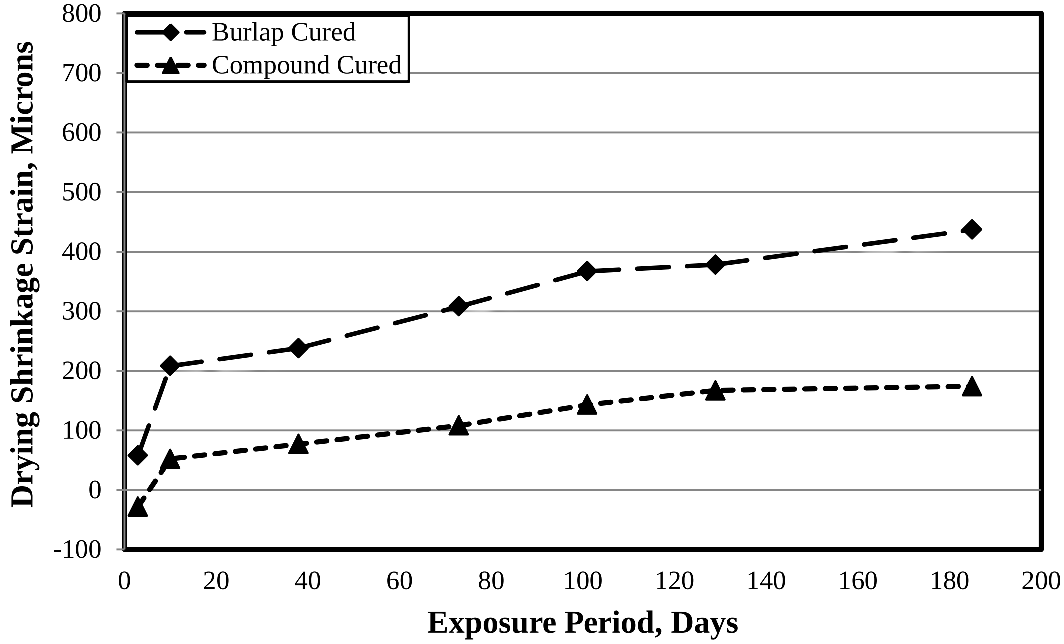

Figure 4.143: Drying Shrinkage Strain in NP Cement Concrete Prepared with w/cm Ratio of 0.4 and Cast at 38°C.

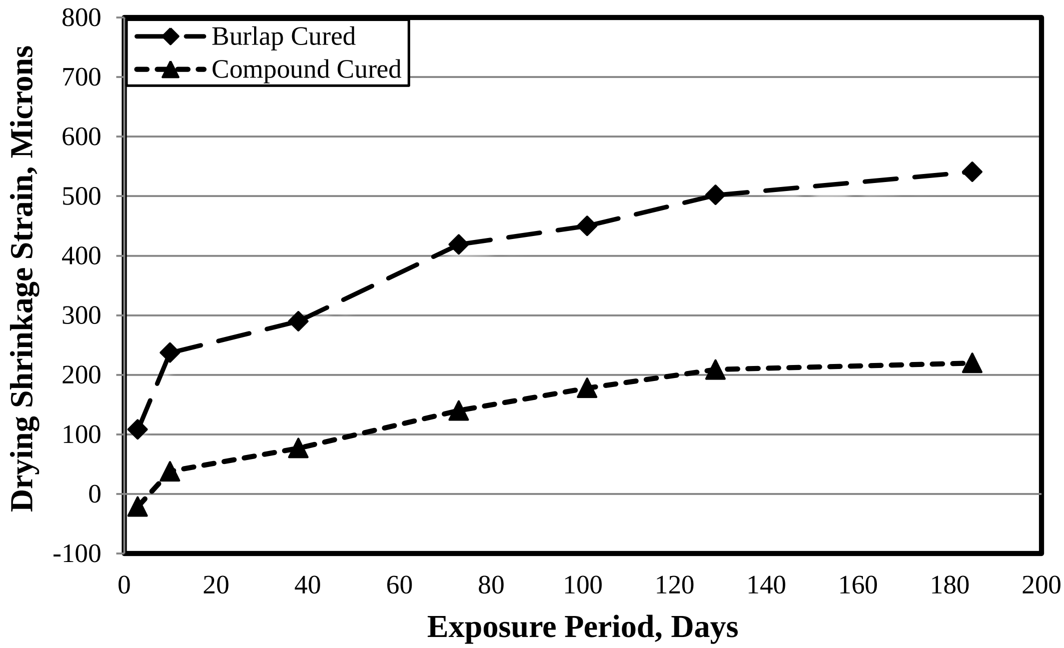

Figure 4.144: Drying Shrinkage Strain in NP Cement Concrete Prepared with w/cm Ratio of 0.4 and Cast at 45°C.

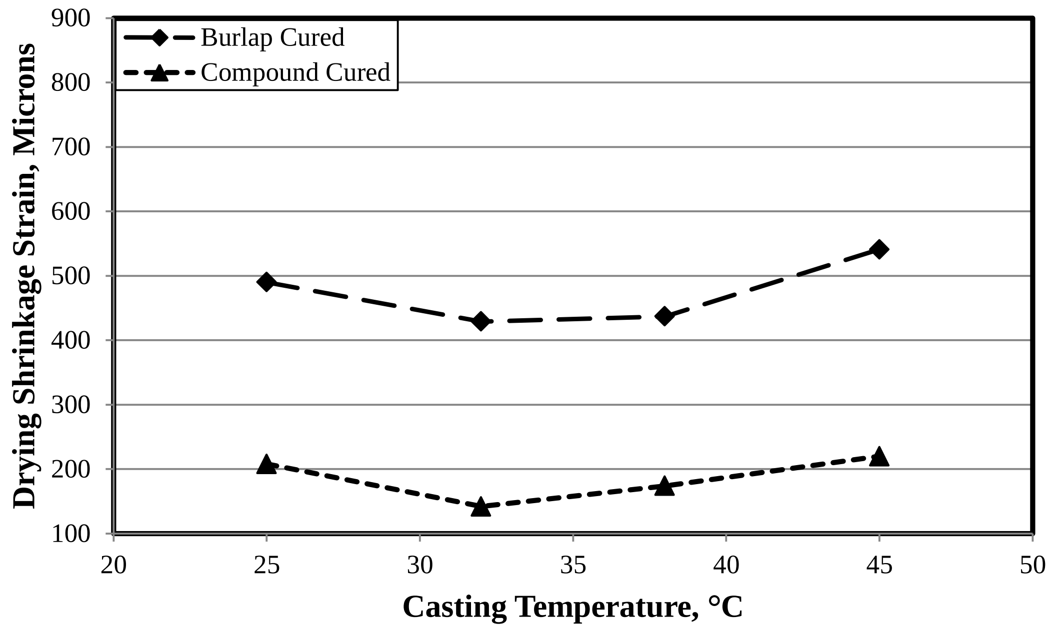

Figure 4.145: Maximum Drying Shrinkage Strain in NP Cement Concretes.

4.6.7 Comparison of Drying Shrinkage Strain in Cementitious Materials

Figures 4.146 and 4.147 depict the maximum drying shrinkage strain in plain and blended cement concrete specimens prepared with a constant w/cm ratio of 0.4, cast at 25 to 45°C and cured by applying a curing compound and covering with wet burlap. The highest drying shrinkage strain was recorded in all concrete specimens cast at 25°C. An exception to this trend was noted in SF and NP cement concretes in which the greatest shrinkage strain was observed at 45°C but it was comparable to strain at 25°C. Further, the shrinkage strain in OPC concretes was more or less similar at 25 and 45°C. On Contrary, the lowest drying shrinkage strain was noted in all concrete specimens cast at 32°C except SF and NP concrete specimens in which the lowest shrinkage strain was recorded at both 32 and 38°C with a marginal difference.

Irrespective of curing regime utilized, the largest value of the maximum drying shrinkage strain was measured in the GGBFS cement concrete specimens cast at 25, 32 or 38°C, while the maximum shrinkage strain at 45°C was noted in the OPC concretes. However, minimum strain was recorded in NP and FA cement concretes cast at 25 or 38°C and 32 or 45°C, respectively.

The data in Table 4.21 shows the ratio of the 185-day drying shrinkage strain in blended cement concretes to that in OPC concretes for a range of average of casting temperatures and curing regimes. The ratio of VFFA to OPC concretes was in the range of 0.90-1.31 (indicating that the maximum value of drying shrinkage strain in VFFA cement concrete was about 10% lesser than OPC concrete at the casting temperature of 38°C, while it was 31% higher than OPC concrete at 32°C). The range of ratio of FA, SF, GGBFS and NP to OPC concrete was 0.76-1.10, 0.74-1.28, 0.92-1.61, and 0.68-1.10, respectively. The lowest value of the ratio of maximum drying shrinkage strain was noticed in NP cement concretes, whereas the highest value of the ratio of maximum drying shrinkage strain was observed in GGBFS cement concretes. Al-Gahtani [7] reported that the ratio of drying shrinkage strain in VFFA, SF and FA cement concrete to OPC concrete specimens cured by covering with wet burlap for 7 days or applying a water-based curing compound was on average 1.02, 0.96 and 0.88, respectively, after about 120 days. Maslehuddin et al. [79] noted that the drying shrinkage strain in SF cement concrete was about on average 40% higher than OPC concrete at about 200 days. Incorporating fly ash and blast furnace slag in blended cements increases shrinkage by 20% with former material and about 60% at very high content of slag [127]. Bao-guo et al. [76] reported that after 28 days of moist curing at 20°C; under higher humidity, the drying shrinkage is reduced due to more refined pore structure of mortar with silica fume while under different environmental conditions, the drying shrinkage is increased due to increase in porosity of mortar with fly ash. Silica fume significantly increases the long-term shrinkage of concrete [128]. Hooton [129] reported that shrinkage is large in SF cement concrete, typically 15% higher shrinkage is measured as compared to neat OPC concrete.

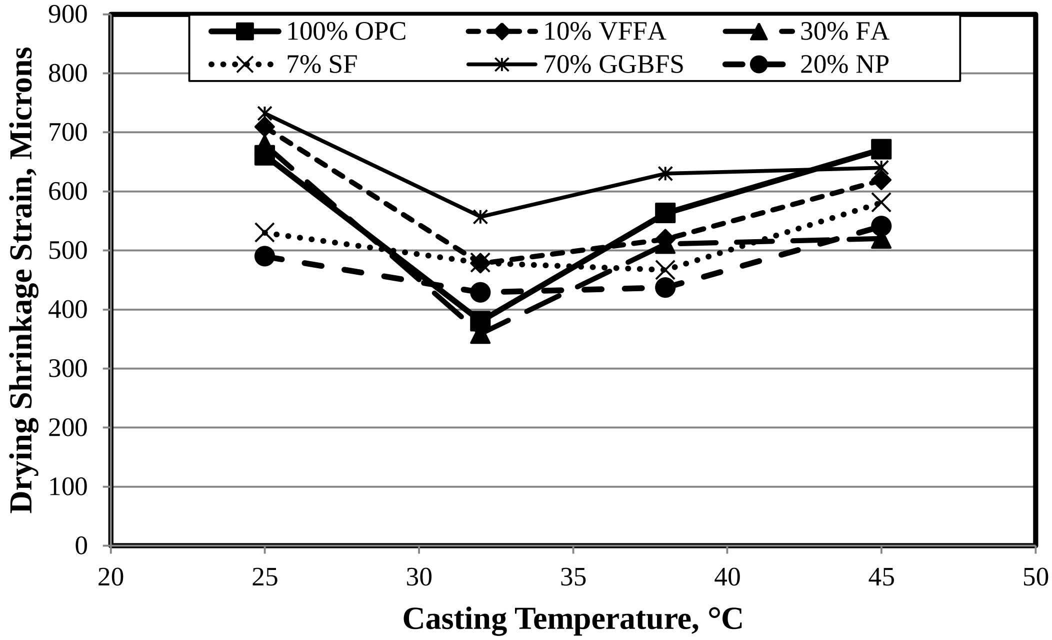

Figure 4.146: Maximum Drying Shrinkage Strain in OPC and Blended Cement Concretes Prepared with w/cm Ratio of 0.4 and Cast at 25-45°C after Applying a Curing Compound.

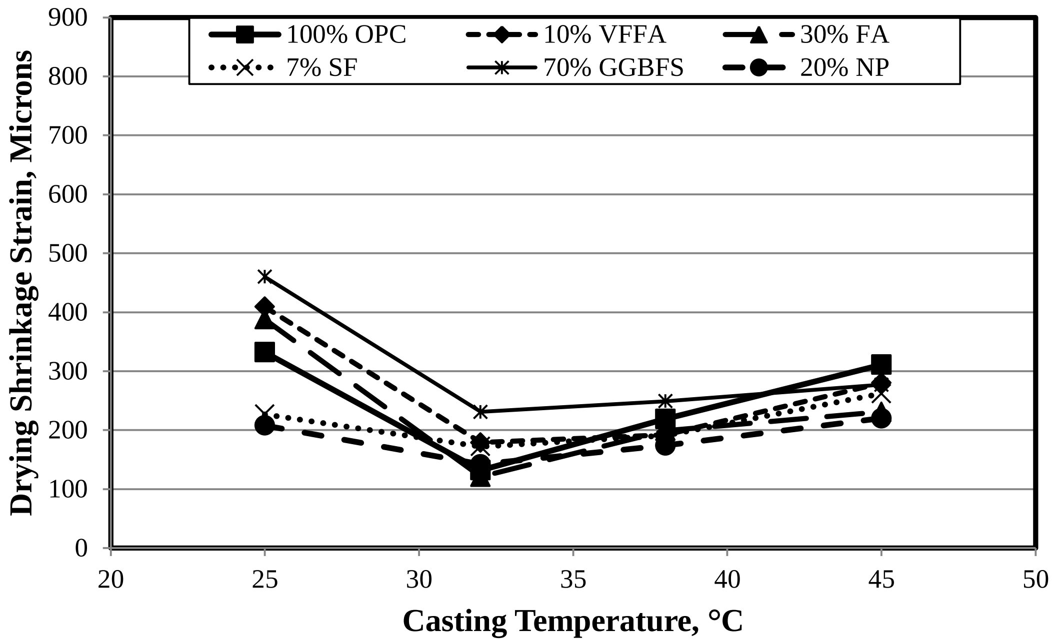

Figure 4.147: Maximum Drying Shrinkage Strain in OPC and Blended Cement Concretes Prepared with w/cm Ratio of 0.4 and Cast at 25-45°C after Curing by Covering with Wet Burlap.

4.7 Statistical Analysis

4.7.1 Mathematical Relationship between Test Properties and Concrete Mix Parameters

The data developed in this study for compressive and split tensile strength, pulse velocity and depth of water penetration were statistically analyzed using Statistica 7 [130] and Minitab 16 [131] softwares to generate numerical expressions between these test properties and concrete mix parameters such as casting temperature, duration of curing and/or water to cement ratio. The 2nd degree mathematical equations formed (due to the non-linear effect of casting temperature on mechanical properties and durability and also for greater accuracy) are generalized as follows:

$$f_c = a + b\left(\frac{w}{c}\right) + c\left(\frac{w}{c}\right)^2 + d\ (T) + e\ (T)^2 + f\ (t) + g\ (t)^2 \quad \text{for OPC concrete} \quad (4.1)$$

$$f_c = a + b\ (T) + c\ (T)^2 + d\ (t) + e\ (t)^2 \quad \text{for blended cement concrete} \quad (4.2)$$

$$f_t = a + b\left(\frac{w}{c}\right) + c\left(\frac{w}{c}\right)^2 + d\ (T) + e\ (T)^2 + f\ (t) + g\ (t)^2 \quad \text{for OPC concrete} \quad (4.3)$$

$$f_t = a + b\ (T) + c\ (T)^2 + d\ (t) + e\ (t)^2 \quad \text{for blended cement concrete} \quad (4.4)$$

$$PV = a + b\left(\frac{w}{c}\right) + c\left(\frac{w}{c}\right)^2 + d\ (T) + e\ (T)^2 + f\ (t) + g\ (t)^2 \quad \text{for OPC concrete} \quad (4.5)$$

$$PV = a + b\ (T) + c\ (T)^2 + d\ (t) + e\ (t)^2 \quad \text{for blended cement concrete} \quad (4.6)$$

$$DP = a + b\left(\frac{w}{c}\right) + c\left(\frac{w}{c}\right)^2 + d\ (T) + e\ (T)^2 \quad \text{for OPC concrete} \quad (4.7)$$

$$DP = a + b\ (T) + c\ (T)^2 \quad \text{for blended cement concrete} \quad (4.8)$$

where a, b, c, d, e, f and g are the constants. The constants for each cementitious material and curing regime along with their corresponding coefficient of correlation (R^2) are summarized in Tables 4.22 to 4.25.

The values of regression coefficient R^2 for all the cementitious materials investigated were more than 0.80, indicating a good correlation between the experimental and predicted data [132]. These numerical equations could be utilized to assess compressive and split tensile strength, pulse velocity and depth of water penetration of plain and blended cement concretes knowing the w/c ratio, casting temperature and curing period under moist condition, curing by covering with wet burlap or applying a curing compound.

4.7.2 Mathematical Relationship between Compressive Strength and Other Test Properties

The correlation between compressive and split tensile strength, compressive strength and pulse velocity and compressive strength and depth of water penetration were established, as shown in Figures 4.148 to 4.150. A good correlation between these properties were noted; R^2 being more than or approximately equal to 0.80 for most of the cases. To arrive at a higher value of R^2, the data points exhibiting higher coefficient of variation in GGBFS cement concrete from pulse velocity and depth of water penetration were excluded while pulse velocity data at 180 days of curing were also not considered in the development of relationship (the reasons of this behavior is discussed under Section 4.3). The simple linear regression analysis conducted to investigate the relationships yields the best-fit models for both plain and blended cement concretes and are expressed as follows:

$f_c = 19.091\,(f_t) - 19.31$ $R^2 = 0.93$ for plain and blended cement concrete (4.9)

$f_c = 0.1065\,(PV) - 423.26$ $R^2 = 0.84$ for plain and blended cement concrete (4.10)

$f_c = -0.406\,(DP) + 58.68$ $R^2 = 0.78$ for plain and blended cement concrete (4.11)

4.7.3 Combined Mathematical Models

The change in properties of concrete usually affects the experimental results and therefore, the use of one method alone would not be suitable to evaluate the required property. For example, the values of pulse velocity increases with age but the change is very small because the density of concrete remains almost constant with the increase in age and, hence, pulse velocity cannot be used alone to predict the compressive strength [133]. The assessment of compressive strength of concretes with greater accuracy and reliability can be possible by combining more than one test property, when all the results pooled together. Multiple regression analysis was carried out to correlate the measured compressive strength with split tensile strength, pulse velocity and depth of water penetration. An excellent correlations between the fitted parameters were observed by having R^2 of about 0.90. The following expressions are obtained for estimating the compressive strength from the developed database utilizing all parameters investigated:

$$f_c = -16.0 + 19.2\,(f_t) - 0.00088\,(PV) \qquad R^2 = 0.93 \qquad (4.12)$$

$$f_c = 11.8 + 11.5\,(f_t) - 0.170\,(DP) \qquad R^2 = 0.92 \qquad (4.13)$$

$$f_c = -43.6 + 0.0221\,(PV) - 0.268\,(DP) \qquad R^2 = 0.90 \qquad (4.14)$$

$$f_c = -19.2 + 8.04\,(f_t) + 0.00976\,(PV) - 0.176\,(DP) \qquad R^2 = 0.90 \qquad (4.15)$$

Table 4.22: Constants and Regression Coefficients for OPC and Blended Cement Concretes for Evaluating Compressive Strength.

Cementitious Materials	Curing Regime	Constant							R^2
		a	b	c	d	e	f	g	
100% OPC	Moist	-9.915	29.683	-138.333	2.732	-0.038	0.491	-0.002	0.942
	Burlap	-16.8630	-13.9667	-71.3333	3.4105	-0.0482	0.4377	-0.0016	0.927
	Compound	-27.3039	3.4500	-93.0000	3.6928	-0.0520	0.4370	-0.0016	0.930
OPC + 10% VFFA	Moist	-29.8555	3.1266	-0.0416	0.5685	-0.0020	-	-	0.961
	Burlap	-45.2487	3.8061	-0.0500	0.5204	-0.0018	-	-	0.957
	Compound	-46.7167	3.8102	-0.0508	0.5178	-0.0018	-	-	0.950
OPC + 30% FA	Moist	-55.9196	4.6251	-0.0652	0.5867	-0.0020	-	-	0.946
	Burlap	-65.8540	5.0075	-0.0697	0.5455	-0.0019	-	-	0.937
	Compound	-75.7188	5.4780	-0.0766	0.5450	-0.0019	-	-	0.937
OPC + 7% SF	Moist	-24.5058	3.1824	-0.0447	0.5026	-0.0017	-	-	0.947
	Burlap	-29.8291	3.3709	-0.0473	0.4485	-0.0015	-	-	0.937
	Compound	-34.4631	3.5676	-0.0507	0.4369	-0.0015	-	-	0.928
OPC + 70% GGBFS	Moist	-44.5268	3.6545	-0.0509	0.5120	-0.0017	-	-	0.962
	Burlap	-48.6950	3.8333	-0.0536	0.4728	-0.0016	-	-	0.948
	Compound	-51.6810	3.8336	-0.0533	0.4504	-0.0015	-	-	0.937
OPC + 20% NP	Moist	-24.6797	2.5391	-0.0331	0.5082	-0.0017	-	-	0.974
	Burlap	-26.0721	2.5478	-0.0337	0.4956	-0.0017	-	-	0.967
	Compound	-29.7510	2.5860	-0.0337	0.4892	-0.0017	-	-	0.967

Table 4.23: Constants and Regression Coefficients for OPC and Blended Cement Concretes for Evaluating Split Tensile Strength.

Cementitious Materials	Curing Regime	Constant							R^2
		a	b	c	d	e	f	g	
100% OPC	Moist	1.77124	-0.67667	-4.33333	0.09736	-0.00128	0.02088	-0.00007	0.929
	Burlap	2.03372	0.41335	-5.43355	0.06041	-0.00075	0.01897	-0.00006	0.933
	Compd.	1.32096	2.66435	-9.03403	0.07912	-0.00105	0.01942	-0.00007	0.927
OPC + 10% VFFA	Moist	0.84827	0.09225	-0.00115	0.02343	-0.000079	-	-	0.94
	Burlap	0.22375	0.11945	-0.00153	0.02288	-0.000078	-	-	0.917
	Compd.	0.03359	0.12518	-0.00163	0.02263	-0.000075	-	-	0.921
OPC + 30% FA	Moist	-1.17751	0.20049	-0.00280	0.02714	-0.00009	-	-	0.962
	Burlap	-0.58330	0.15494	-0.00214	0.02642	-0.000087	-	-	0.959
	Compd.	-0.86963	0.16702	-0.00238	0.02651	-0.000088	-	-	0.953
OPC + 7% SF	Moist	0.73788	0.11764	-0.00165	0.02111	-0.000069	-	-	0.918
	Burlap	0.75433	0.10706	-0.00148	0.01848	-0.000055	-	-	0.912
	Compd.	0.18901	0.14290	-0.00211	0.01753	-0.000052	-	-	0.9
OPC + 70% GGBFS	Moist	-1.73027	0.21161	-0.00293	0.02464	-0.00008	-	-	0.936
	Burlap	-2.12702	0.22952	-0.00318	0.02154	-0.00007	-	-	0.918
	Compd.	-2.42617	0.24229	-0.00341	0.02129	-0.00006	-	-	0.912
OPC + 20% NP	Moist	0.07141	0.10123	-0.00122	0.02707	-0.000091	-	-	0.949
	Burlap	-0.70176	0.13384	-0.00169	0.02764	-0.000093	-	-	0.938
	Compd.	-0.40403	0.10534	-0.00128	0.02861	-0.000100	-	-	0.938

Table 4.24: Constants and Regression Coefficients for OPC and Blended Cement Concretes for Evaluating Pulse Velocity.

Cementitious Materials	Curing Regime	Constant							R^2
		a	b	c	d	e	f	g	
100% OPC	Moist	4305.090	-448.333	-766.667	14.698	-0.205	3.521	-0.015	0.899
	Burlap	3981.03	368.33	-1833.33	22.39	-0.31	3.04	-0.01	0.92
	Compound	3619.83	2823.33	-5333.33	17.43	-0.24	2.68	-0.01	0.935
OPC + 10% VFFA	Moist	3794.336	21.256	-0.220	4.859	-0.021	-	-	0.931
	Burlap	3708.454	25.733	-0.297	4.384	-0.019	-	-	0.939
	Compound	3862.095	16.335	-0.176	3.922	-0.018	-	-	0.935
OPC + 30% FA	Moist	3304.328	51.671	-0.703	5.008	-0.021	-	-	0.859
	Burlap	3332.682	48.822	-0.670	4.545	-0.019	-	-	0.863
	Compound	3394.777	44.023	-0.604	4.048	-0.018	-	-	0.858
OPC + 7% SF	Moist	3952.165	21.457	-0.297	4.825	-0.021	-	-	0.866
	Burlap	4025.442	15.366	-0.220	4.335	-0.019	-	-	0.87
	Compound	4105.865	9.167	-0.132	3.866	-0.018	-	-	0.839
OPC + 70% GGBFS	Moist	2647.336	69.812	-0.967	5.191	-0.021	-	-	0.899
	Burlap	2381.086	82.980	-1.154	5.326	-0.023	-	-	0.854
	Compound	2532.077	73.438	-1.022	5.076	-0.022	-	-	0.834
OPC + 20% NP	Moist	3466.951	38.187	-0.473	4.022	-0.017	-	-	0.955
	Burlap	3569.387	30.522	-0.363	3.597	-0.015	-	-	0.937
	Compound	3650.395	24.495	-0.286	3.313	-0.015	-	-	0.938

Table 4.25: Constants and Regression Coefficients for OPC and Blended Cement Concretes for Evaluating Depth of Water Penetration.

Cementitious Materials	Curing Regime	Constant a	Constant b	Constant c	Constant d	Constant e	R^2
100% OPC	Moist	214.811	-350.833	583.333	-7.991	0.115	0.883
	Burlap	231.075	-500.000	800.000	-6.863	0.101	0.916
	Compound	184.754	-159.167	316.667	-7.007	0.103	0.864
OPC + 10% VFFA	Moist	140.6259	-6.3603	0.0879	-	-	0.904
	Burlap	155.0846	-6.5162	0.0879	-	-	0.996
	Compound	193.7732	-8.0822	0.1099	-	-	0.971
OPC + 30% FA	Moist	210.7167	-10.3938	0.1484	-	-	0.955
	Burlap	227.6940	-10.9520	0.1593	-	-	0.974
	Compound	253.6438	-11.7809	0.1703	-	-	0.967
OPC + 7% SF	Moist	155.0759	-7.6052	0.1099	-	-	0.968
	Burlap	179.0624	-8.4065	0.1209	-	-	0.943
	Compound	181.8741	-7.7565	0.1099	-	-	0.970
OPC + 70% GGBFS	Moist	115.5998	-3.8606	0.0495	-	-	0.698
	Burlap	131.7123	-4.1718	0.0549	-	-	0.776
	Compound	163.2265	-5.6186	0.0769	-	-	0.781
OPC + 20% NP	Moist	159.7843	-6.8871	0.0934	-	-	0.999
	Burlap	159.6626	-6.3327	0.0879	-	-	0.972
	Compound	214.7896	-9.0067	0.1264	-	-	0.939

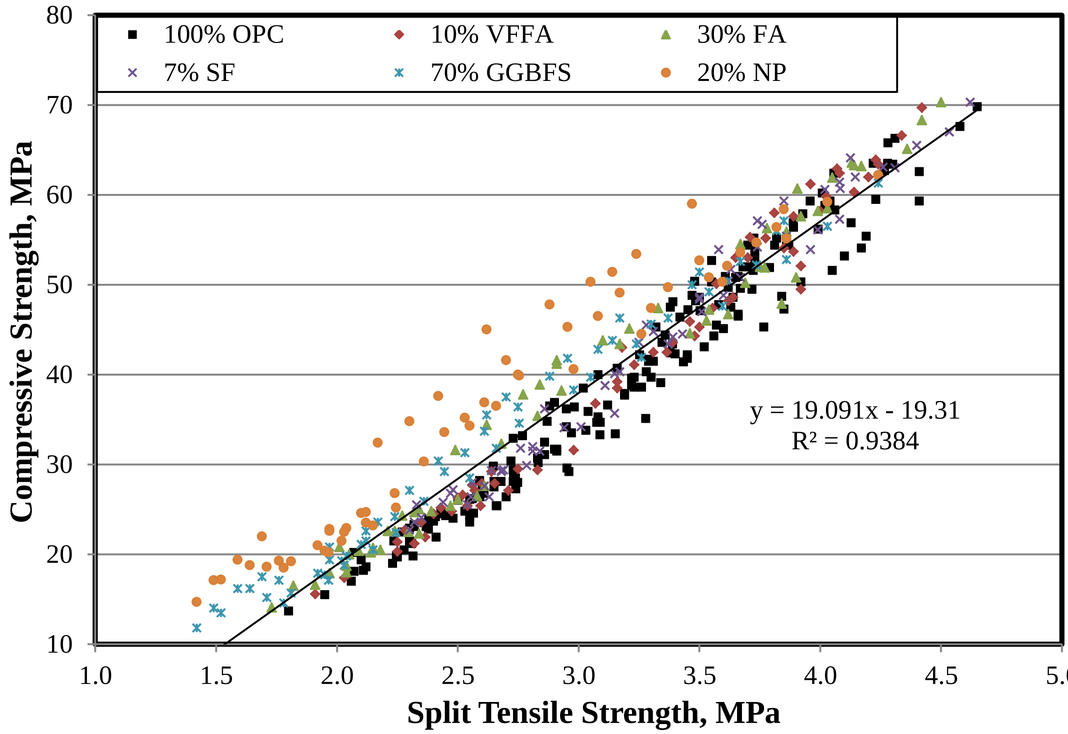

Figure 4.148: Correlation between Compressive and Split Tensile Strength for all OPC and Blended Cement Concretes.

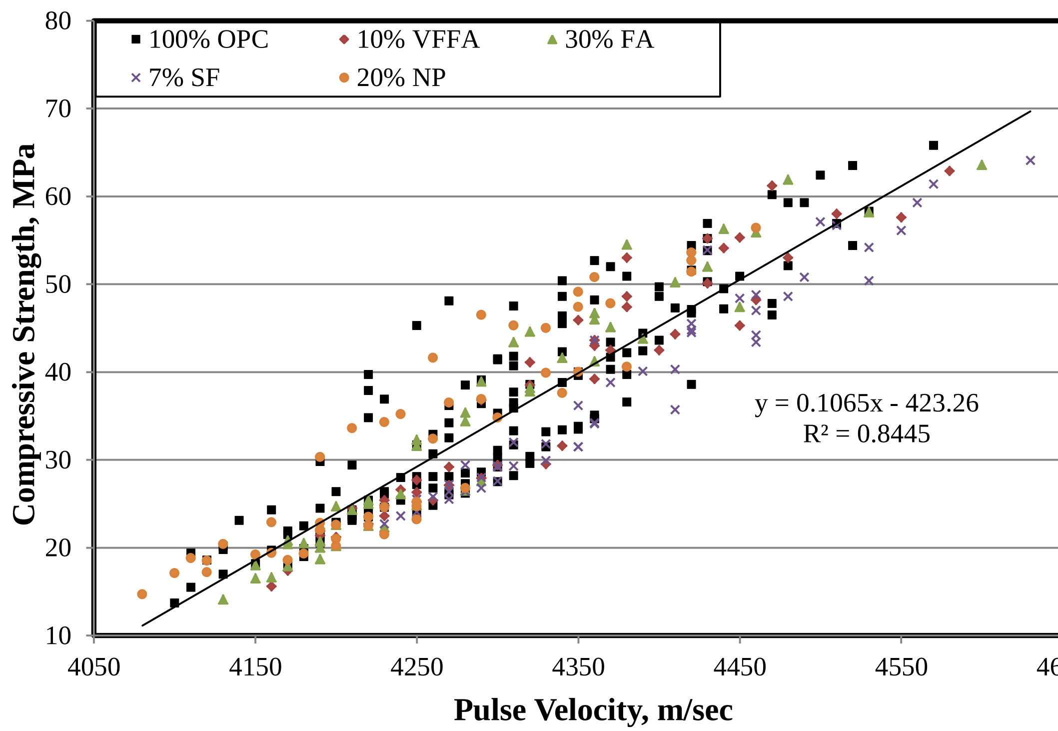

Figure 4.149: Correlation between Compressive Strength and Pulse Velocity for all OPC and Blended Cement Concretes.

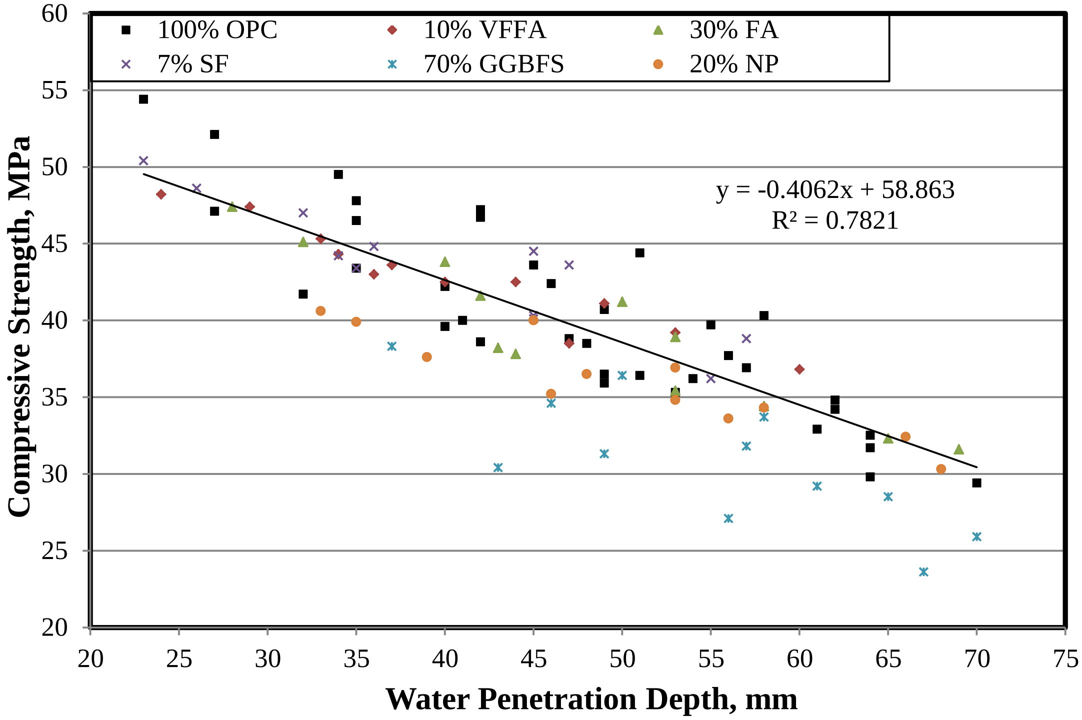

Figure 4.150: Correlation between Compressive Strength and Depth of Water Penetration for all OPC and Blended Cement Concretes.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

This research was carried out to assess the effect of casting temperature and curing regime on the mechanical properties, durability and shrinkage characteristics of concretes whereby six types of cementitious materials i.e. Type I (OPC), very fine fly ash (VFFA), fly ash (FA), silica fume (SF), ground granulated blast furnace slag (GGBFS) or natural pozzolan (NP), three water to cement ratios (0.3, 0.4 or 0.45 for 100% OPC concretes while 0.4 for blended cement concretes), four casting temperatures (25, 32, 38 or 45°C), four curing regimes (water ponding, wet burlap, curing compound or plastic sheet) were used. The following conclusions could be drawn based on the data developed in this comprehensive study:

5.1.1 Compressive Strength, Split Tensile Strength and Pulse Velocity

i. The compressive and split tensile strength and pulse velocity increased with age in all the concrete specimens. An exception to this trend was noted in the pulse velocity which slightly decreased after 180 days in all concrete specimens. The increase in strength (compressive and split tensile) and pulse velocity was very rapid in the early age of up to 28 days and 90 days in OPC and blended cement concretes, respectively. Thereafter, the increase in strength was not that significant.

ii. The strength and pulse velocity in OPC and blended cement concrete specimens cured under moist condition were more than those in the specimens cured by covering with wet burlap or applying a curing compound. Further, the strength and pulse velocity in the concrete specimens cured by covering with wet burlap was more than that in the specimens cured by applying a curing compound.

iii. As expected, the strength and pulse velocity in the concrete specimens prepared with 100% OPC decreased with an increase in the w/c ratio.

iv. Irrespective of the w/c ratio and/or curing regime, the strength and pulse velocity increased with temperature up to 32°C. However, a further increase in the casting temperature decreased the strength and pulse velocity in the OPC and SF cement concretes. An exception to this trend was noted in FA, VFFA, NP and GGBFS cement concretes. In these concretes, the strength and pulse velocity continued to increase up to a temperature of 38°C; thereafter, there was a decrease in these properties.

5.1.2 Depth of Water Penetration

i. The minimum depth of water penetration was noted in OPC and blended cement concretes cured under moist condition followed by those that were cured by covering with wet burlap, while the depth of water penetration in the concrete specimen cured by applying a curing compound was the highest.

ii. As expected, the depth of water penetration in concrete specimens prepared with 100% OPC increased with an increase in the w/c ratio.

iii. Irrespective of w/c ratio and/or curing regime, the depth of water penetration decreased with temperature up to 32°C. However, a further increase in the casting temperature increased the depth of water penetration. An exception to this trend was noted in FA, VFFA, NP and GGBFS cement concretes. In these concretes, the depth of water penetration continued to decrease up to a temperature of 38°C; thereafter, there was an increase in the depth of water penetration.

5.1.3 Plastic Shrinkage Strain

i. The plastic shrinkage strain increased with time in all the OPC and blended cement concrete specimens and most of the plastic shrinkage occurred within about the initial 8 hours of curing. Thereafter, the increase in the plastic shrinkage strain was not that significant. However, the plastic shrinkage strain in all concrete specimens stabilized nearly to a constant value after about 14 hours.

ii. The plastic shrinkage strain in OPC and blended cement concrete specimens cured by the application of curing compound was lower than that in the specimens cured in air.

iii. As expected, the plastic shrinkage strain in the concrete specimens prepared with 100% OPC increased with an increase in the w/c ratio.

iv. Irrespective of w/c ratio and/or curing regime, the maximum plastic shrinkage strain was recorded in all the OPC and blended cement concrete specimens cast at 25°C followed by those cast at 32 or 45°C, while the minimum plastic shrinkage strain was measured at either 32 or 38°C. An exception to this trend was noticed in GGBFS cement concrete specimens in which, plastic shrinkage strain decreased with an increase in the temperature but there was a marginal difference between shrinkage strain at 38 and 45°C.

5.1.4 Drying Shrinkage Strain

i. The drying shrinkage strain increased very rapidly in the early ages in all the OPC and blended cement concrete specimens and most of the drying shrinkage occurred within about 130 days of exposure after curing. Thereafter, the increase in strain was not that significant. However, the drying shrinkage strain in all the concrete specimens was stabilized nearly to a constant value after about 185 days.

ii. The drying shrinkage strain in OPC and blended cement concrete specimens cured by the application of a curing compound was less than that in the concrete specimens cured by covering with wet burlap.

iii. As expected, the drying shrinkage strain in the concrete specimens prepared with 100% OPC increased with an increase in the w/c ratio.

iv. Irrespective of w/c ratio and/or curing regime, the maximum drying shrinkage strain was recorded in all the OPC and blended cement concrete specimens cast at 25°C. An exception to this trend was noted in OPC, SF and NP cement concretes in which the maximum drying shrinkage strain was measured at both 25 or 45°C with marginal difference. However, the minimum drying shrinkage strain was noted in all the OPC and blended cement concrete specimens cast at 32°C. An exception to this trend was noted in SF and NP cement concretes in which the minimum drying shrinkage strain was recorded at both 32 or 38°C with a slight difference.

In summary, the mechanical properties and durability and shrinkage characteristics were noted to be influenced by all the parameters investigated. Unlike the specifications of ACI Committee 305 and Saudi Building Code 304-C regarding 35°C as the limit for the maximum allowable fresh concrete temperature at the time of placement, the results of this study indicated that the optimum temperature for OPC and SF cement concrete was 32°C. However, for VFFA, FA, GGBFS and NP cement concretes, the optimum casting temperature was 38°C. Further, moist curing was found to be beneficial in strength and pulse velocity development as well as for enhancing the durability; followed by curing by covering with wet burlap and applying a curing compound, in decreasing order. However, the application of a curing compound on fresh concrete exhibited higher efficiency in reducing the plastic and drying shrinkage strain as compared to curing by covering with wet burlap or plastic sheet. Moreover, the highest plastic and drying shrinkage strain was noted in almost all concrete specimens cast at 25°C. However, a further increase in the temperature decreased the shrinkage strain.

5.2 Recommendations

From the above conclusions, the following recommendations could be drawn for improving the mechanical properties and durability characteristics of concrete structures when concreting is commenced under hot weather:

i. Curing with wet burlap should be preferred over the application of curing compound whenever and wherever possible.
ii. Low w/c ratio for OPC concretes can be used if the workability is maintained.
iii. The limit for maximum allowable fresh concrete temperature of plain and blended cement concretes at the time of placement should be as follows:

Cementitious Materials	Optimum Temperature (°C)
OPC	32
SF	32
VFFA	38
FA	38
GGBFS	38
NP	38

iv. The correlations developed in this study could be used to evaluate the compressive and split tensile strength, pulse velocity and depth of water penetration by knowing the w/c ratios, casting temperature and curing period for particular cementitious materials and curing regimes. Moreover, by evaluating one property the other concrete properties can be determined from the relationships obtained.

Further, for enhancing the shrinkage resistant efficiency of plain and blended cement concrete structures, the application of a curing compound should be preferred compared with curing by covering with wet burlap or plastic sheet, whenever possible. Moreover, precautionary measures such as those recommended by ACI Committee 305 may be taken to minimize the difference between the concrete casting temperature and ambient temperature, particularly under hot weather.

5.3 Future Studies

Following are the recommendations for future research:

- Performance of other water retaining techniques like: acrylic-based curing compound, bitumen-based curing compound, coal tar epoxy, etc. under hot weather need to be assessed.
- Combination of curing methods like curing the specimens with wet burlap for few days and then applying a curing compound under hot weather need to be studied.
- Effect of hot weather on the microstructure and reinforcement corrosion needs to be investigated.
- Long-term data for mechanical and durability properties of concrete with supplementary cementitious materials to examine the optimum casting temperature need to be determined.
- The optimum casting temperature using ternary and quaternary cement concretes utilizing the waste materials needs to be evaluated.

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